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EXPERIMENTAL INVESTIGATIONS ON HYBRID CONICAL DIFFUSER WITH DISTORTED INLET CONDITIONS

by

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Experimental Investigations on Hybrid Conical Diffuser with Distorted Inlet Conditions

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To
my Parents

CERTIFICATE

This is to certify that the present work entitled Experimental Investigations on Hybrid Conical Diffuser with Distorted Inlet Conditions *was carried out by* Kuldeep Kumar Tyagi *under my supervision and it has not been submitted elsewhere for a degree.*

10.5.95

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- KULDEEP KUMAR TYAGI

ABSTRACT

A hybrid diffuser consisting of vortex controlled step and diverging passage has considerable merits for applications as a precombuster. In hybrid diffuser, a part of the main flow is sucked through the Vortex chamber at the throat of the diffuser.

Present investigations are mainly concerned with the effect of different inlet conditions on a hybrid diffuser. The geometrical parameters have been constant throughout the investigations. These inlet conditions have been changed with radial, circumferential distortions. A mild swirl motion at inlet has also been discussed. Results show that the hybrid diffuser with uniform velocity profile is most efficient. Circumferential distortion has most severe effect on the performance of the diffuser. The swirl at the inlet reduces the performance of the hybrid diffuser but improves pressure recovery in simple diverging passage.

NOMENCLATURE

A_1	Cross section area at diffuser inlet
A_2	Cross section area at base of vortex controlled step
A_3	Cross section area at diffuser exit
AR	Overall area ratio
B	Percentage of mainstream flow which is sucked out through the vortex
C_p	Coefficient of static pressure recovery
D_1	Diameter at diffuser inlet
D_2	Diameter at base of vortex controlled step
D_3	Diameter at diffuser exit
K_δ	Inclination factor in meridian plane
K_ψ	Inclination factor in equatorial plane
$\dot{m}_1$	mass flow rate at inlet
p_1	Static pressure at diffuser inlet
p_2	Static pressure at diffuser exit
p_c	Static pressure inside the vortex chamber
R	Radius of the crossection
r	radial station of the crossection
S	swirl intensity
U_{av1}	Mass average axial velocity at the inlet
U_{av}	Mass average axial velocity
U_{max}	Maximum axial velocity
V_c	Coefficient of vortex chamber depression
V_r	Velocity parameter in circumferential distortion
X	Axial gap between inlet duct and vortex retaining fence
Y	Radial gap between inlet duct and vortex retaining fence
α_1	Kinetic energy correction factor at inlet
α	guide vane angle in swirler
ρ	Density of air at test section
θ	Total divergence angle of the diffuser cone
ϕ	Fence subtended angle
PSI	Angular location in the crossection
δ	Angle of the pitch
ψ	Angle of yaw

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Chapter 1

Introduction

Efficient pressure recovery at the expense of dynamic head is an important consideration in the design of diffusers.In aircraft gas turbine engine the flow velocity is usually high at the compressor exit.However to reduce pressure losses,the velocity in the combustor should be low.So diffuser is used in between compressor and the combustor. But this diffusion process is usually not efficient. To have a large pressure recovery in a short length a larger divergence angle is required. With large divergence angles flow seperation causes a low pressure recovery and nonuniform velocity distribution at the exit.

For subsonic flow , a diffuser would have an increasing area.Some typical geometries are conical, annular ,square and rectangular diffusers.The blade passage in an axial compressor is essentially a diffuser. Diffuser exit flow influences the combustor performance also. So a good diffuser should not only have a greater pressure recovery in short length but also with as uniform exit conditions as possible.

The performance of a diffuser depends on both geometrical and flow parameters. Geometrical parameters include diffuser angle,area ratio,shape of the diffuser,inlet length to width ratio and turning angle (in case of curved diffusers).The flow parameters that affect the performance are Reynold and Mach numbers at the inlet, the free stream turbulence level and the inlet velocity profile.

The parameter which is most important and the major factor that governs the

static pressure gradient along the diffuser is the diffuser divergence angle.For the simple diverging case, optimum angle should be in the range 7 to 9 degrees.For a particular value of length to inlet dia. ratio Moore and Kline (4) envisaged four different flow regimes as the angle of divergence is increased.These broadly classified regimes consist of (a) a regime of well behaved flow with no appreciable stall (b)a regime of large transitory stall in which separation varies in position, extent and intensity (c) a regime of fully developed stall in which major portion of diffuser has large triangular shaped recirculation region and (d)a jet flow regime in which the main flow is separated from both walls.Performance depends more factors than flow pattern and is dominated by different geometrical parameters in different regimes.For example,pressure recovery is dominated by area ratio in the installed regime,by diverging angle in the large transitory stall regime and by no geometric parameter in two dimensional stall and jet flow regime.Although these regimes were for rectangular diffuser,but they are expected to provide a conservative approach to the conical diffuser also.

A short diffuser is more prone to seperation.So it has to be controlled by some method which can energize the boundary layer.This can be achieved by means of vortex generators.Boundary layer mixing caused by vortex delays the separation.Splitter vanes can be used to disturb the stream line as to avoid/delay seperation.Tangential blowing can also be used to energize the tired boundary layer. Boundary layer suction in a wide angle diffuser through a chamber creating a vortex which imparts momentum to the slow moving fluid in boundary layer, can give a good pressure recovery and at the same time enable to monitor the exit velocity profile.This particular technique of improving diffuser performance is the topic of present investigations and is described below in more detail.

1.1 Concept of Vortex Controlled Diffuser

A jet engine diffuser designer looks for minimum pressure loss, uniform air flow properties at the exit of diffuser, short length to reduce the overall engine length and

weight.In this connection vortex controlled diffuser seems to satisfy most of the above said needs of a gas turbine diffuser. The concept of vortex controlled diffuser was first described by Ringlib (3).Main aim was to reduce the boundary shear stresses experienced by the flow in the region of adverse pressure gradient.The aerodynamic design of cusps would be such as to locate vortices in the direction of main flow .The main problem with this arrangement was to maintain a stable vortex system, as energy would be lost within the cusps by skin friction.

However,the design of vortex controlled diffuser proposed by Adkins (1) over comes this problem by bleeding off some percentage of the main flow through a seperate chamber just at the exit of primary duct and maintaining a stable vortex. This component is called a vortex chamber (Fig.1). The mechanism of maintaing a vortex chamber is shown in Fig.2. Suppose there is some suction through the vortex chamber.Then the stream tube "a" is drawn into vortex chamber due to reduced pressure and accelerates as it approaches the chamber entrance. The stream tube "b" continues to flow through the diffuser and decelerates (as it is moving in a region of greater static pressure) appreciably in the region of vortex chamber. As a result of this , turbulent shear action is produced between the two stream i.e an extremely turbulent layer is created due to the shearing action produced by the velocity differential between the two streams.This gives rise to energy transfer from the stream "a" to stream "b", thereby helping stream "b" to flow through the diffuser without seperation.That means some of the fluid in the stream "b" which would have less energy for further diffusion is thus able to flow through the diffuser without stall developing.

Further downstream of the throat, one more vortex formation takes place in the direction of primary flow, due to the formation of Coanda Bubble (Fig.2) and this also helps in avoiding or delay in seperation.

But minimum bleed rate to have optimum performance was one constraint.Hybrid diffuser was designed with reduced minimum bleed rate requirement .In case of hybrid diffuser vortex controlled step accounts for a small increase in cross sectional area and would therefore require a minimum bleed off .Turbulent layer generated by the step is instrumental in avoiding the flow seperation from a relatively wide angle conventional

diffuser.

1.2 The Typical Performance of Vortex Controlled Diffuser

The diffuser performance is usually expressed in terms of either the coefficient of static pressure recovery or the diffuser effectiveness. A typical performance curve in terms of diffuser effectiveness as a function of bleed off is shown in Fig.3.Three distinct regions can be seen here. In the initial region a to b, there is a unsufficient suction and air is drawn into the suction chamber only from the low velocity in the lee of the fence. This gives rise to a slight increase in pressure recovery. Region b to c is a development region where there will be enough depression in the vortex chamber as to deflect the mainstream. This causes the increase in pressure recovery. Here there is a continious air flow into the vortex chamber.Region c to d shows almost constant diffuser performance. In this case vortex has already been stabilised and mainstream has achieved a stagnation point. Point c is termed as the minimum bleed off requirement condition. After point c mechanism is said to be stable.

1.3 Review of Literature

Considerable attention has been given to literature regarding the turbine diffuser and in particular relevant to axial compressure discharge. Literature regarding control of diffuser outlet profile and the performance of combustor at various exit profiles was also studied.

Seno and Nishi (5) were able to avoid flow seperation by using vortex generators. Vortex generators which consists of small blades were applied to conical diffuser the diverging angle of which were 8, 12, 16, 20 and 30 degree with area ratio four.The experiment covered the influence of various parameters, such as arrangement of blades , inlet boundary layer thickness and location of vortex generator relative to the conical diffuser on pressure recovery coefficient. It was stipulated that trailing vortices from

vortex generators provided an induced component perpendicular to the wall to delay or prevent boundary layer seperation in an adverse pressure gradient. By using vortex generators , flow fluctuation of wall pressure was reduced for divergence angle less than or equal to 16 degree. Introduction of tail pipe seemed to have improved the pressure recovery .It was inferred that for thick boundary layer at inlet , there would be provision to improve the coefficient for static pressure recovery with vortex generators.

Donald et al, (6) studied the effects of radial and circumferential distortion at inlet velocity profiles on the performance of a short length annular ram induction combustor. Exit temperature distribution was severely affected by circumferential distortion.

Improvement in the technology of the compressor and combustor component of the gas turbine engine have in recent years placed a greater emphasis upon the requirement for a short efficient diffuser between these components. Adkins (1) developed vortex controlled diffuser with suction chamber through which air is bleed off. The diffuser entry Mach number and velocity profile distortion levels in these experiments were simulated to those encountered in the engine system. He inferred that a pressure in excess of 80% may be obtained with diffuser length only one third of conventional diffuser using a bleed off rate of approximately 5% of the main flow at the diffuser throat. Later on , Adkins et al (2), working on hybrid arrangment reduced the bleed rate requirement.The outcome was an efficient diffuser ,half the length of equivalent conical diffuser and which would operate satisfactorily without either bleed off or vane projecting into the flow .Flethcher and Adkins (7) has used the concept of vortex controlled diffuser in tandem with combustion chamber in investigations relating to control of pollutant emissions from gas turbine combustor.They inferred from the experiments that pollutant emission reductions can be achieved by the use of variable geometry.

Adenubi has carried out experimental investigations of the flow regimes and the performance of the straight core annular diffusers operating immediately downstream of an axial compressor.He took into account the different compressor's discharge parameters. Out of these the effect of relative turbulence intensities were comparetively

large and increased along the diffuser. Overall geometrical parameters of area ratio and non dimensional length were concluded the controlling factors in determining the optimum diffuser geometry regardless of diffuser type. An analytical model of the analysis of vortex generators in a fully viscous subsonic flow has been evaluated by Kunik(8).

1.4 Literature Survey for the Velocity Profile Generation

Owen and Zienkowicz(9) obtained a nearly uniform flow in working suction of a wind tunnel by inserting a grid of paralled rods with varying spacing.

The function of such a grid is to impose a resistance to the flow , so graded across the working section as to produce a linear variation in the total pressure at large distances downstream without introducing an appreciable gradient in static pressure near the grid . Although the method for finding the spacing between the grids was for rectangular section , it was expected to give some conservative result for circular section to have a symmetrical radial distortion in the velocity profile.

Study on two dimensional flow through an arbitrary shaped gauzes of nonuniform properties placed in a channel was done by Elder. Livesly and Turner(11) modified the nonuniformity of the upstream flow that seems to have existed in the work of Owen by improved grid spacing . Same method for design of grid has been used to have circumferential distortion. But grid was used only for 1/3 of the circumference. For imparting the swirl motion straight guide vane have been used (12).

1.5 Scope of the Present Work

Diffuser in aero application should have a short length in view of the overall engine size and weight. Dump diffuser were used in oreder to minimise the length of the diffuser. But some limitation are there in dump diffusers due to non uniform air flow properties at the exit and higher pressure losses. Although vortex controlled and

hybrid arrangment (1,2) gave a higher pressure recovery but more efforts are needed in view of the actual inlet condition before it can find application in practical gas turbine engines.

Sullerey, Ashok and Shantharam (4) employed the concept of vortex control on two dimensional diffusers and found that bleed rate requirement in case of centre peaked velocity profile was almost two times that of in case of flat uniform inlet velocity profile.As investigations have been done to find the effect of geometrical parameter on the performance of the diffuser. Here main emphasis has been on the flow parameters at inlet and exit.As exit velocity profile affects the performance of the combustor, efforts have been done to find out the inlet velocity profile to have uniform flow parameters at the exit as well as with minimum bleed rate requirement.

Experiment were done with symmetrical velocity profile without distortion. symmetrical radial distortion,circumferential distortion. Adkins (2) suggested the possibility of working on the effect of the swirl at inlet on the performance of vortex controlled diffuser. In present investigation ,a weak swirl motion at the inlet has also been studied.

Chapter 2

Experimental Set Up and Measurements

Experimental set up consists of mainly two components.First is the air supply system and the tunnel used for present investigations.Second component is diffuser which has been designed and fabricated.The basic set up of tunnel and air supply system available at propulsion laboratory was chosen for present investigation.Cascade tunnel facility was not availed primarily because of the constraint regarding suction requirment at much high volume flow rates.

2.1 The Tunnel

The apparartus consists of a small tunnel (including a contraction and the test section) mounted on an adjustable platform.Fig.4 gives the layout of the tunnel used. The layout consists of a flexible pipe line to supply compressed air ,a settling chamber and contraction. The set up for diffuser consists of primary duct, vortex chamber, diverging portion (conventional diffuser) and tail pipe.

The tunnel section is square starting at 266.7mm and necking down to 83.8mm at the test section.Inside the settling chamber there are flow straightners followed by four sets of the wire screens. The cross-section available at the tunnel is a square. So

to connect it to the primary duct (which is circular), a transition has been designed and fabricated. To connect different parts of the system, flanges of the mild steel has been fabricated.At the position between transition and primary duct one can inserts grids or swirler to alter the inlet conditions. Provision is there to supply air through flexible piping.

2.2 Air Supply System

The detailes of compressed air bottles of the trisonic tunnel from which the the compressed air supply was taken are given below.
Number of the bottles =3
Length of the bottles=10m
Diameter of the bottle=2m
Maximum pressure =1.8 MPa
Total capacity =85cum
Temperature=ambient

The layout of the air supply system from the compressed air bottles upto tunnel is shown in Fig.5.A 63mm internal diameter pipe line connects these air bottles to pressure gauge ,a wheeled stop valve,pressure reducing valve and a safety valve.Inside the laboratory, it passes through another set of pressure reducing valve and pneumatically operated butterfly flow control valve.One more pressure gauge is located near the tunnel.Two stages of pressure reduction is possible through pneumatically controlled pressure regulator valves to obtained the required pressure at the inlet of the tunnel which is about atmospheric.The compressed air for operating these valve is obtained from the same pipe line .

2.3 Design of the diffuser

As in the present investigation,main emphasis has been on flow parameter.Geometrical parameter (Fig.6) have been taken optimum and kept constant (2). Design details of the fabricated part has been shown in Fig.7 Over all area ratio has been kept 2.0 and vortex controlled step accounts for a area ratio (A_2/A_1) of 1.2.The diverging angle (θ) and fence subtended angle (ϕ) have been 25 and 30 degrees respectively.The primary duct ,made of mild steel as internal diameter equal to 105 mm and has a thickness of 2mm.Diameter at vortex controlled step is 115mm and diameter at the exit is 148.5mm. A tail pipe of length 50mm has also been connected to have a better mixing and diffusion. Fence subtented angle (ϕ) is a crucial parameter affecting the performance of the hybrid diffuser. There for extra care has been taken during the fabrication in maintaining the value of X and Y.

2.4 Suction System

A suction system (Fig.8) of capacity of 102cum/hr was employed to enable the boundary layer to be bled off equally from the two points of the chamber.To insure a uniform suction a flange with four slots has been used in the vortex chamber.The suction pump is capable of handling bleed of rates upto 8% of the main flow. Air entry to the vortex chamber is governed by fence subtened angle (ϕ) which is a crucial parameter affecting the performance. diffuser. X and Y (Fig 6) have been kept 7mm and 4mm respectively.

For measureing the amount of the suction , a orificemeter is provided (Fig.8).Bleed off rate control was through a butterfly valve. Diameter of suction pipe was 50.8mm and thickness is 4mm. So outer diamter of the orifice plate was choosen 50mm.Material of the plate is mild steel. The ratio of the internal diameter to the external diameter of the orifice plate be choosen primarily on the consideration of head produced in manometer across the orifice due to bleed air .Based on this ratio and Reynold number coefficient of the discharge was about 0.64 (14).

2.5 Design of the Grid and Swirler

The typical velocity profile at the outlet of an axial compressor is over a range of value of U_{max}/U_{av} from 1.03 to 1.15 (17). In order to generate this profile it was decided to place a grid at the entrance of primary duct.The procedure for design of the grid was according to ref 9 to 11.The same design was used for grid to have circumferential distortion. Spacing between the grid's wire is shown in the Fig.9

Basically three methods are generally followed to design swirler (12).First is the tangential arrangment for the entry of the fluid stream into the main flow.Second is the rotation of some mechanical devices such as rotating vanes or grids into the flow .Third method which has been followed in the present investigation is use of constant angle guide vanes for generation of swirl.The guide vane angle α (Fig10) for swirl intensity of 0.4 was calculated (eq.3.5) to be 30 degrees from the axial direction.

2.6 Diffuser Instrumentation and Measurements

The present experimental investigations consisted of static pressure measurements and evaluation of velocity profiles in the primery duct as well as in the secondary duct.These measurments have been carried out for vortex controlled hybrid diffuser for different bleed off rates and inlet conditions. The present investigations have been done with Reynold number of around 10^5.

The pressure difference across the orifice was measured using a multitube manometer with an accuracy of 1mm of the water. For small bleed rates electronic mannometer with a accuracy of 0.1mm of the water was also used to find out the pressure difference Wall pressure measurements were taken with the help of the electronic manometer.Dynamic head measurements were also taken with the help eletronic manometer using a 1mm dia pitot tube.

In order to ensure the required velocity at the end of the primary duct,a proper control of the flow rate through pneumatically operated butterfly valve was essential.This can be monitored by a pressure regulator located by the side of settling

chamber.To have a constant velocity at the inlet , a correlation was established between the dynamic head at the center of the crossection of the primery duct exit and pressure difference between settling chamber wall pressure just at the entery of primery duct.These corelations were confirmed by large number of repeated readings.

To determine velocity profile at the end of the primery duct and at the exit of the diffuser, pitot tube was used. Difference between total pressure head and static head gives the dynamic head directly on the electronic manometer. Readings were taken at the two mutually perpendicular diameter. More number of readings were taken near the wall where profile is expected to changed or deviate.

In case of circumferential distortion ,measurements were taken at points seperated by a fixed angle interval at a perticular radial station[8].This interval at the inlet and exit was 90 and 45 degrees respectively.To show the distortion a parameter was defined according to Ref 6.(eq.3.3)

For pressure measurements, two pressure tapping were located in each primary duct and vortex chamber at symmetrical locations.Pressure tappings arrangment along the diffuser can be seen in the Fig.7.Pressure tappings were placed at two opposite diameteral locations.Pressure measurements were also taken along the tail pipe. These readings were taken with reference to the primary duct pressure tapping. Vortex chamber was calculated for different beed off rates by vortex chamber pressure tappings.

In suction system, equal amount of bleed was to be created from two symmetrical locations in the vortex chamber. For this, symmetrical connections were taken through a 3/4 inch pipe and were connected to a 'T' joint as in Fig.8. Amount of bleed off air was controlled through the butterfly valve and was measured across the orifice. In order to maintain lower bleed rates a series of holes were drilled at the end of suction pipe just before the connection to suction pump. These holes were to be blocked or sealed if the system has to provide higher bleed offs.

In swirling flow to determine the flow direction , a 5 hole spherical probe was used. To determine the flow angles calibration chart of Ref 16 was used. This calibration charts is shown in Fig.12. By the help of the flow angles,axial and tangential com-

ponents of the flow are determined (Fig.11).Swirl intensity at the inlet and exit was calculated according to eq.3.4 by using the method of numerical integration.

Chapter 3

Performance Calculations

The overall performance of a diffuser is usually evaluated in terms of total pressure loss, coefficient of static pressure recovery (C_p) and quality of exit velocity profile. Although in the present investigations, coefficient of static pressure recovery has been used as a performance measure.

C_p is defined as (Ref 2)

$$C_p = \frac{p_2 - p_1}{\frac{1}{2}\alpha_1 \rho {u_{av1}}^2} \tag{3.1}$$

where,

$$u_{av1} = \frac{\dot{m}_1}{\rho A_1}$$

and

$$\alpha_1 = \frac{n^2 \sum_1^n (\sqrt{h})^3}{(\sum_1^n \sqrt{h})^3}$$

Where h is the measured dynamic head at the inlet and n is the number of traverse points used having equal area weighting.

In many applications when a hybrid diffuser is used,it is necessary to take full account of the losses entailed by bleeding air off.Unfortunately there is no universal term which can be used satisfactorily to provide this assessment.It depends on whether the bleed air is to be simply dumped or it is to be reintroduced back into the flow stream.To enable assessment to be aimed at a particular application the pressure loss experienced by the bleed air is given by the coefficient of vortex chamber depression defined as (Ref 2)

$$V_c = \frac{p_1 - p_c}{\frac{1}{2}\rho\alpha_1 {u_{av1}}^2} \tag{3.2}$$

To detrmine the distortion in a velocity profile $\frac{U_{max}}{U_{av}}$ was determined by the method of numerical integration.

In circumferentially distorted profile,velocity parameter(V_r) is defined as (Ref 6)

$$V_r = \frac{v_{r\,loc} - v_r}{v_r} \tag{3.3}$$

Where $v_{r\,loc}$ is the velocity at a particular angular position and particular radial station where as v_r is the average of the velocity at all angular locations.

In case of swirling motion swirl intensity S in terms of the flow parameter is defined as (Ref 12)

$$S = \frac{\int_0^R \rho w u 2\pi r^2\, dr}{\int_0^R \rho u^2 2\pi r\, dr} \tag{3.4}$$

Where u and w are axial and tangential velocities in the swirling flow.

For a straight vane swirler vane angle α (Fig.10) is given as follows (Ref 12)

$$\tan\alpha = S \times \frac{3}{2}\left[\frac{1 - (\frac{R_h}{R})^3}{1 - (\frac{R_h}{R})^2}\right] \tag{3.5}$$

Where S is the swirl intensity of the flow. R_h and R are hub radius and shell radius, respectively.

To find out the different components of the air in swirling flow,five hole probe was used. The theory of the five hole spherical pitot tube is based upon the energy equation between a point in the free stream and on the surface of the sphere. To determine the direction of the flow two angles have been defined in two planes (Fig.11). One is the angle of pitch (δ) in the meridian plane and another is angle of yaw (ψ) in equatorial plane. For any given point on the sphere the inclination factors have been defined as follows (Ref 15)

$$K_\delta = \frac{h_1 - h_2}{h_1 - h_4} = f(\delta, \psi) \tag{3.6}$$

$$K_\psi = \frac{h_1 - h_3}{h_1 - h_5} = f(\psi, \delta) \tag{3.7}$$

Where h_1,h_2..... are the pressure reading of the five hole on the probe.Calibration chart from Ref 16 was used to determine the flow angles (Fig.11)

Chapter 4

Results and Discussion

The present experimental investigations were mainly concerned with performance of vortex controlled hybrid conical diffuser at various inlet conditions and bleed off rates. Optimum geometrical parameters have been taken from the previous investigations of Adkins and kept constant. Main emphasis has been on the inlet conditions. Experiments were carried out with inlet velocity profile without any distortion, radial distortion, circumferential distortion and with a mild swirling motion (S=0.34) at the inlet.In each case optimum performance, vortex chamber depression and exit velocity profile were determined.In addition individual contributions of of vortex controlled step and diverging passage in over all pressure recovery have also been investigated.

4.1 Inlet Velocity Profile without Distortion

Adkins (1) trying to develop a short diffuser with low pressure recovery, investigated the performance of a diffuser with vortex controlled step . He found that although bleeding improves the performance substantially, a high bleed rate of more than 5.0 % was required to achieve this performance. This diffuser met the requirement for a precombuster application.

Later on Adkins (2) worked on hybrid arrangement and found that the minimum bleed rate requirment can be reduced . In hybrid arrangement minimum bleed

rate was about 2 %. Investigation were done with symmetrical inlet profile without distortion to verify these results.

Without any distortion optimum performance was about 0.71 (C_p) at 2.2 % bleed rate (Fig.13). Vortex chamber depression which shows the pressure loss in the bleed air was found to increase with bleed rate (Fig.18). This is consistant with the results of Adkins.

Pressure measurements were also taken to show the performance of the diffuser along the axial length (Fig.14) These measurements show that suction improves the performance of vortex controlled step as well as of diverging passage. But at higher bleed rate the contribution due to diverging passage is predominant.At the inlet, velocity profile was quite uniform (U_{max}/U_{av} =1.04)(Fig.19) and at exit , it was distorted(U_{max}/U_{av} = 1.28)(Fig.20) Suction not only improves the performance but also reduces the distortions. At 2.2 % bleed rate, distortion at exit was reduced with U_{max}/U_{av} equal to 1.23 (Fig.21).

4.2 Inlet Velocity Profile with Radial Distortion

Seldom the velocity profile at the outlet of an axial compressor is uniform and hence tests have to be carried out with distorted velocity profiles. Typical value of U_{max}/U_{av} at the exit of axial compressor is 1.1 (17). A symmetrical grid has been designed to provide a nonuniform inlet velocity profile and U_{max}/U_{av} was found to be 1.17 (Fig.22).

As non-unform flow is more prone to separation, with this profile optimum performance was found to be 0.7(C_p)(Fig.13). In addition the minimum bleed rate requirement was found to be 3.2 % (Fig.13). Vortex chamber depression showed similar trend and increases with bleed rate (Fig.18) Measurements along axial the length shows that suction improves the overall pressure recovery but individual contribution of vortex controlled step and diverging portion were almost unaffected by suction at inlet (Fig.15). Here also suction accomodated the distortion. At 0 % bleed rate

U_{max}/U_{av} at the exit was 1.47 (Fig.23). But at 3.2 % bleed rate, profile became more uniform with $U_{max}/U_{av} = 1.35$ (Fig.24).

4.3 Inlet Velocity Profile with Circumferential distortion

At axial compressor exit ,due to randomness in stalled and unstalled flow, there is some circumferential distortion in the velocity profile. According to Schultz and Perkins (6), among various distorted profile, circumferential distortion was the only profile that affected the exit temperature distribution in combustor severely. To have circumferential distortion, same grid was used but only for 1/3 of the circumference. With circumferential distortion U_{max}/U_{av} at inlet was found to be 1.62 (Fig.25) As axial velocity distribution was non-uniform and severely distorted, the performance of the diffuser decreases appreciably. With this kind of distortion, pressure recovery was least among all distorted inlet flow for all possible bleed rates. With optimum performance the value of the cofficient of static pressure recovery was found only 0.36 and minimum bleed rate requirment was 3.2 % (Fig.13) Vortex chamber depression increases with bleed rate. Measurements along axial length (Fig.16) shows that individual contribution of vortex controlled step and diverging portion in pressure recovery were unchanged with suction. At the exit, at 0 % bleed rate velocity profile was severly distorted with $U_{max}/U_{av} = 1.82$ (Fig.26). Suction of 3 % of the main flow reduces its nonuniformity to $1.71(U_{max}/U_{av})$ (Fig.27).

4.4 Diffuser Performance with Mild Swirl Motion at Inlet

When flow comes out of the compressor, it has a mild swirl($S < 0.4$). Although swirler was designed for S=0.4 but swirl intensity at the inlet was calculated as 0.34 and U_{max}/U_{av} was found to be 1.58 (Fig.28). The performance of hybrid arrangement

was better than with other inlet condition at 0 % bleed rate. But suction at inlet failed to improve pressure recovery significantly. With suction its optimum performance was 0.40(C_p) (Fig.13). Minmum bleed rate requirment was approximately 3.3 % (Fig.13).

Vortex chamber depression increases with bleed rate in the same pattern. Axial distribution of the pressure recovery shows that swirl reduced the pressure recovery along the vortex controlled step (Fig.17). Probably it was due to the low pressure zone created by the swirling flow. But pressure recovery along the diverging passage was very good . At the exit, velocity profile was more distorted. U_{max}/U_{av} at the exit at 0 % bleed rate was 1.9(Fig.29) but 3.3 % suction of the main flow makes it more uniform with $U_{max}/Uav = 1.47$ (Fig.30). Without suction swirl intensity also was found to decrease to 0.12. At 3.3 % bleed rate, swirl intensity at exit was found to be approximately equal to 0.04.

4.5 Comparision among various Inlet Conditions

To have a clear understanding of effects of inlet conditions on diffusion process in a hybrid arrangement, a comparative study was done (Fig.13). It can be referred from the Fig.13 at first sight that distortion of any kind at inlet profile lowers the performance of the diffuser. It was worst with circumferential distortion and best with no distortion. It was due to non-uniformity in the flow, which is more prone to separation. Radial distortion has a very little effect on the performance of the diffuser. But minimum bleed rate requirement was higher. Vortex chamber depression was found to increase with suction rate in all cases. But it was highest in case of circumferential distortion. Without suction swirl at inlet gives a better performance than other cases.In swirling flows, vortex controlled step's contribution was lesser than other cases.

Chapter 5

Conclusion

1. Hybrid diffuser is most efficient with uniform inlet velocity profile.

2. Among all Distortions, circumferential distortion has most severe effect on the pressure recovery of vortex controlled diffuser.

3. Minimum bleed rate requirement is also minimum with uniform inlet velocity profile.

4. Swirl at inlet has detrimental effect on the performence of vortex controlled diffuser and hybrid diffuser.

5. Swirl at inlet may help in improving the pressure recovery in a simple diverging passage.

6. Tail pipe improves the effectiveness of diffuser in all cases.

7. Vortex chamber depression increases with bleed rate for all inlet velocity profile.

8. Suction not only improves the performence of diffuser but also impoves the exit velocity profile for combustor performence.

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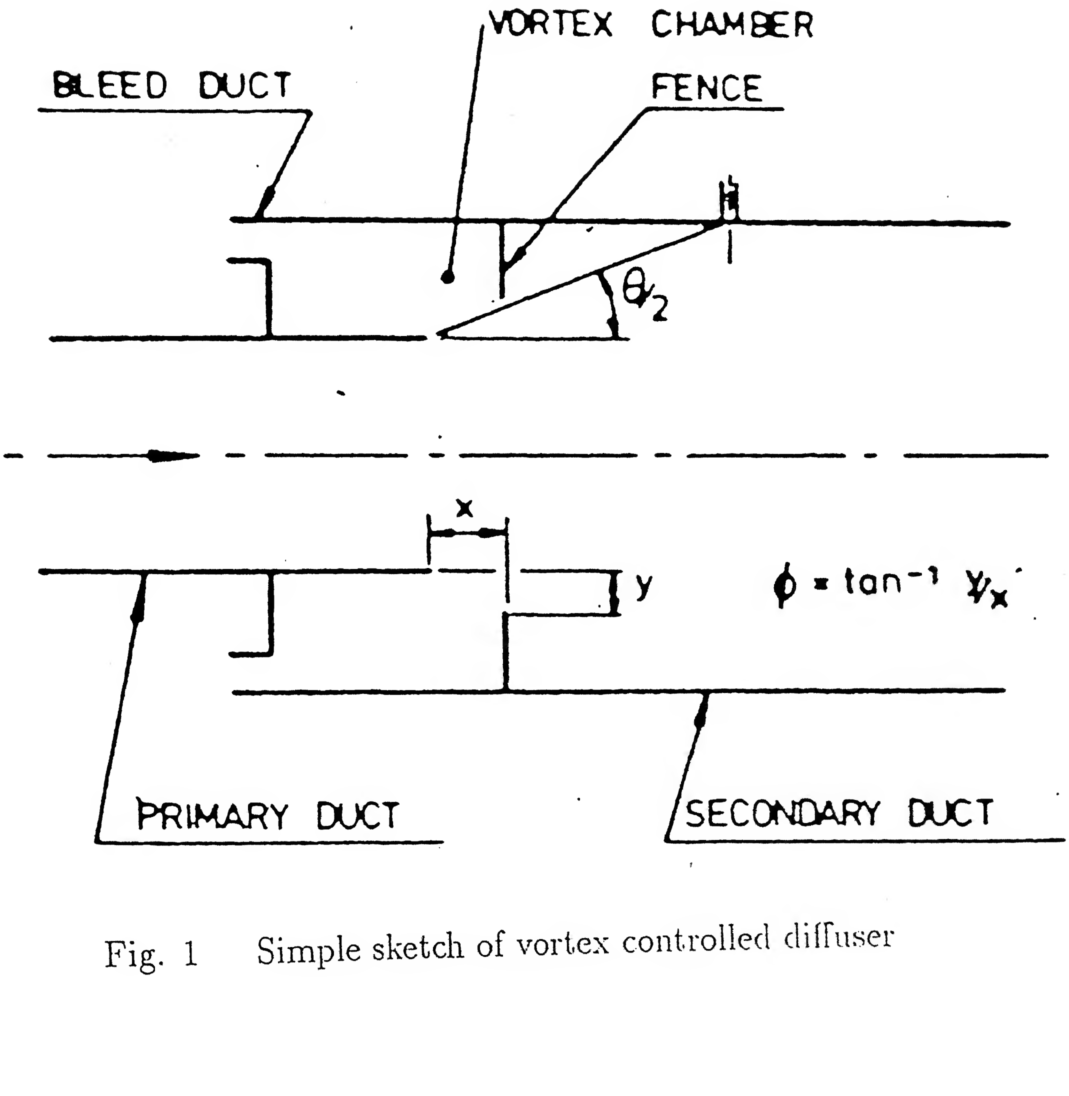


Fig. 1 Simple sketch of vortex controlled diffuser

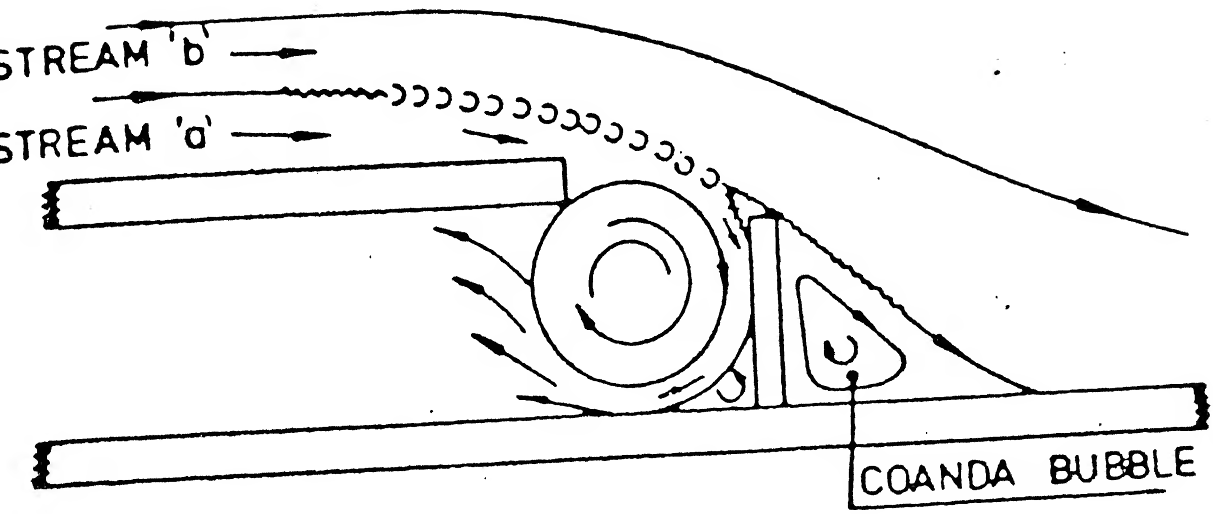


Fig. 2 Flow mechanism of vortex control

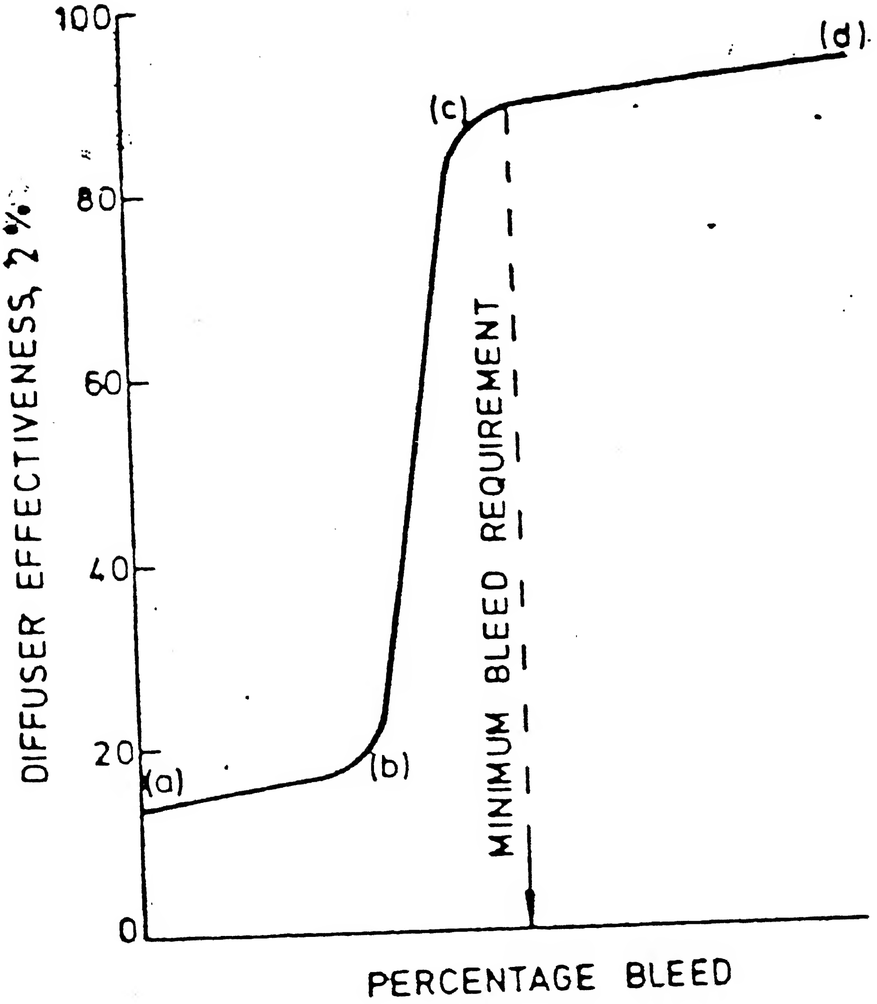


Fig. 3 Typical diffuser characterstic

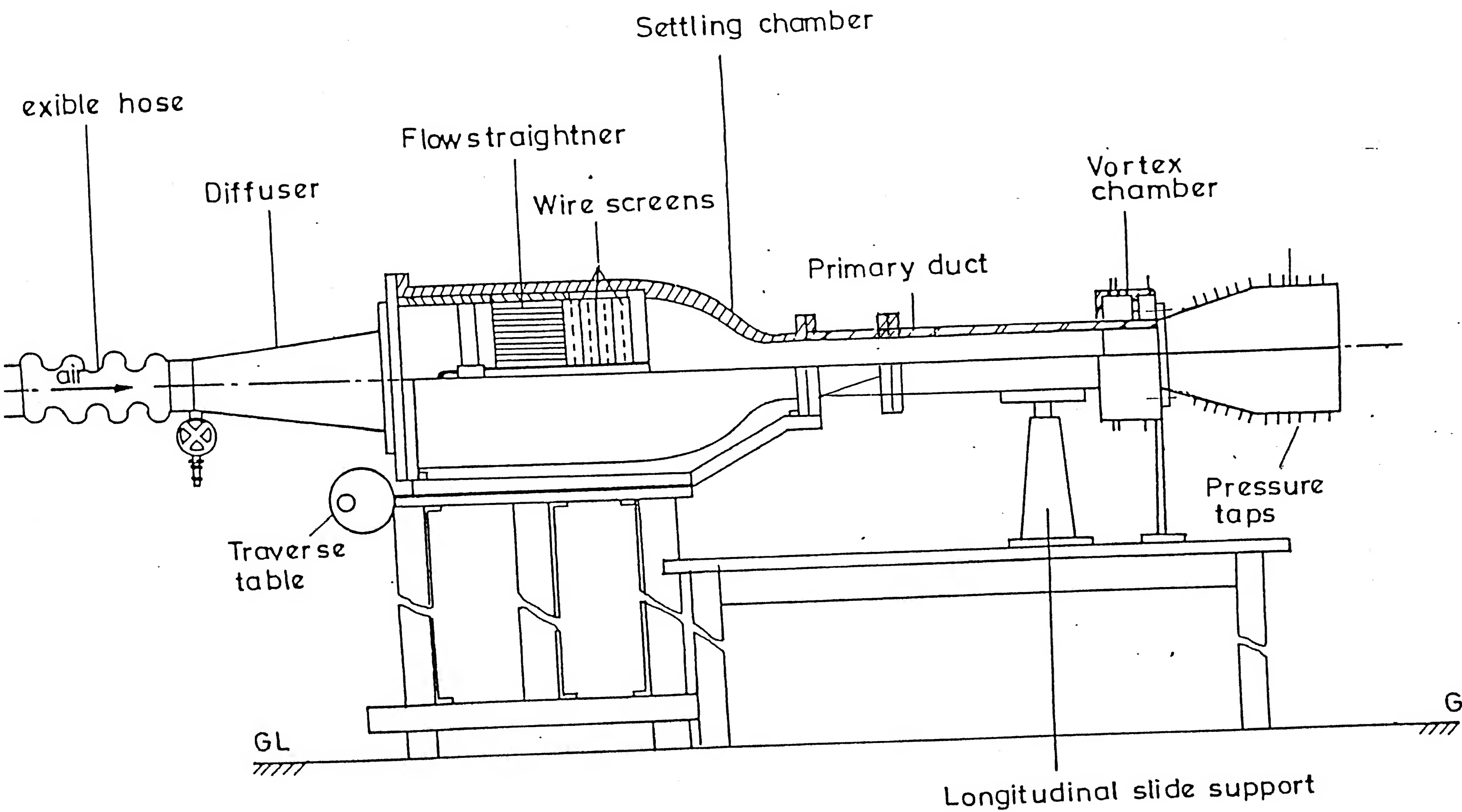


Fig. 4 Layout of the tunnel

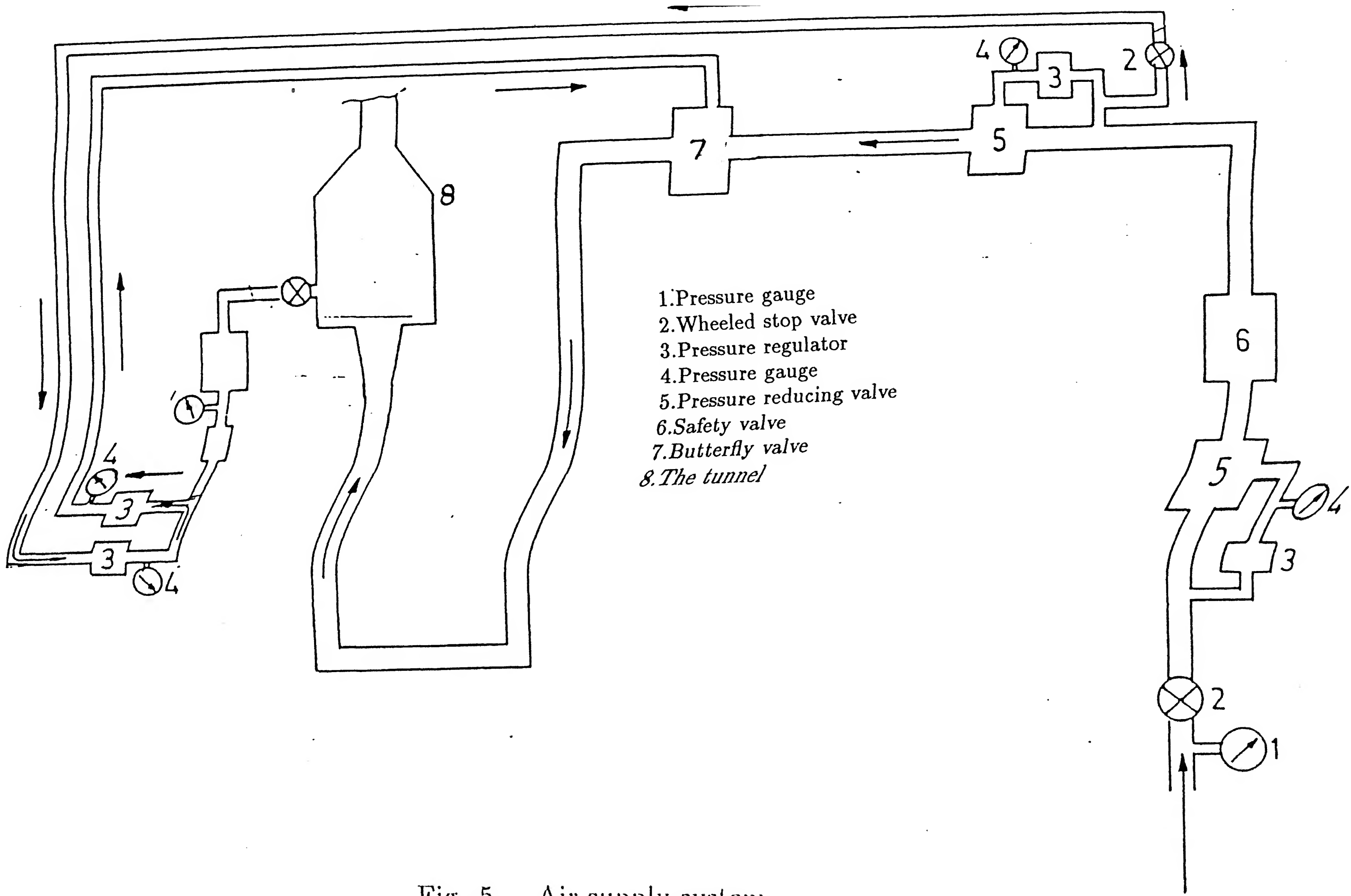


Fig. 5 Air supply system

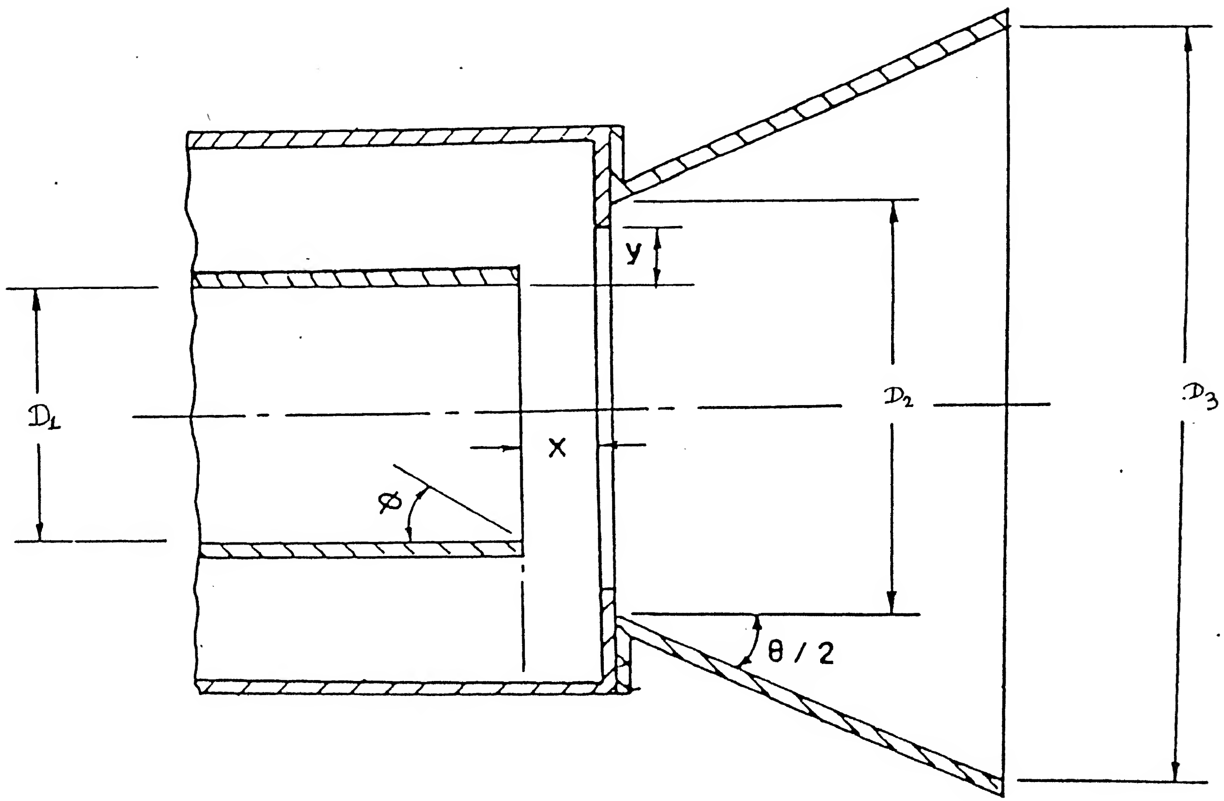


Fig. 6 Geometrical parameters

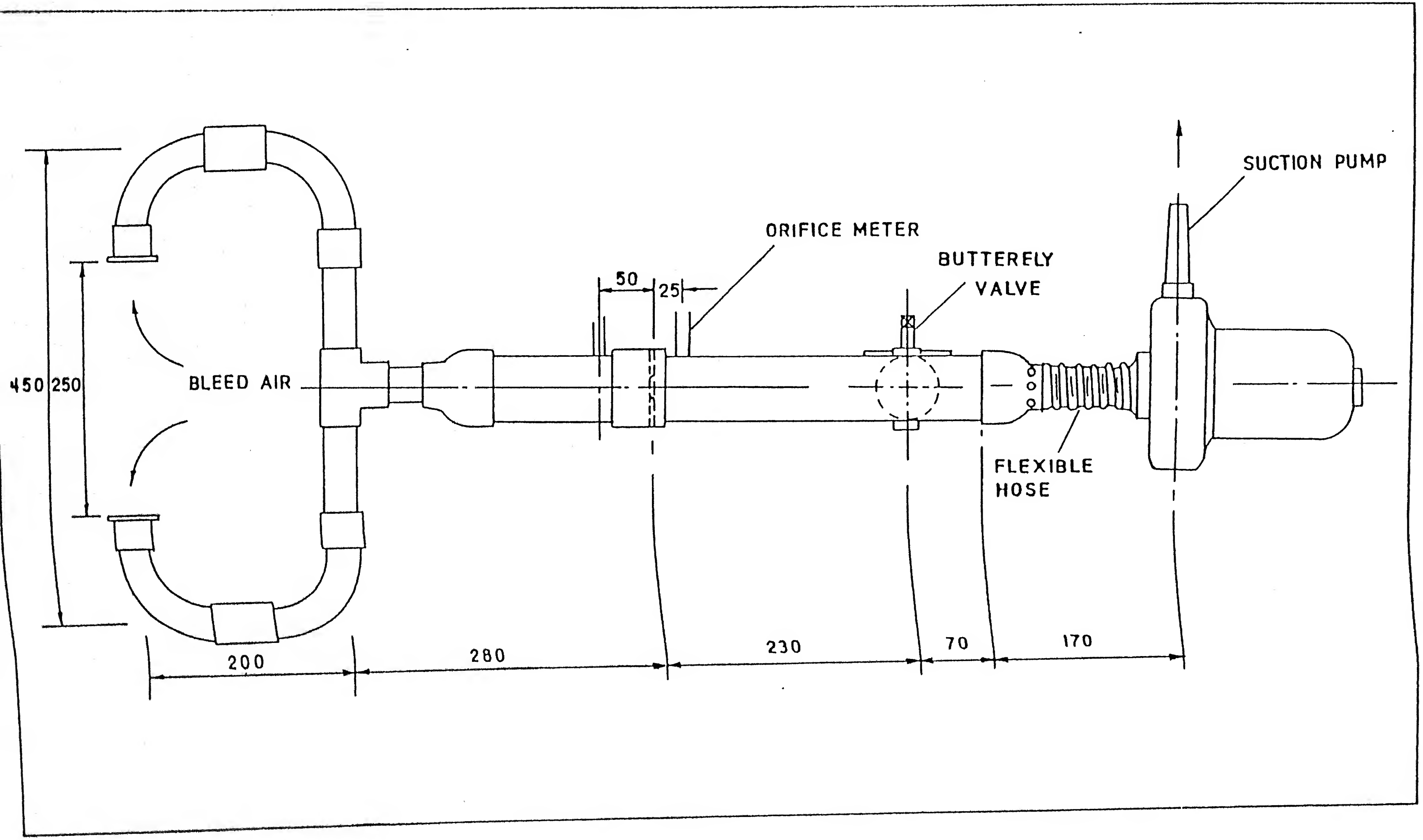


Fig. 8 Suction system

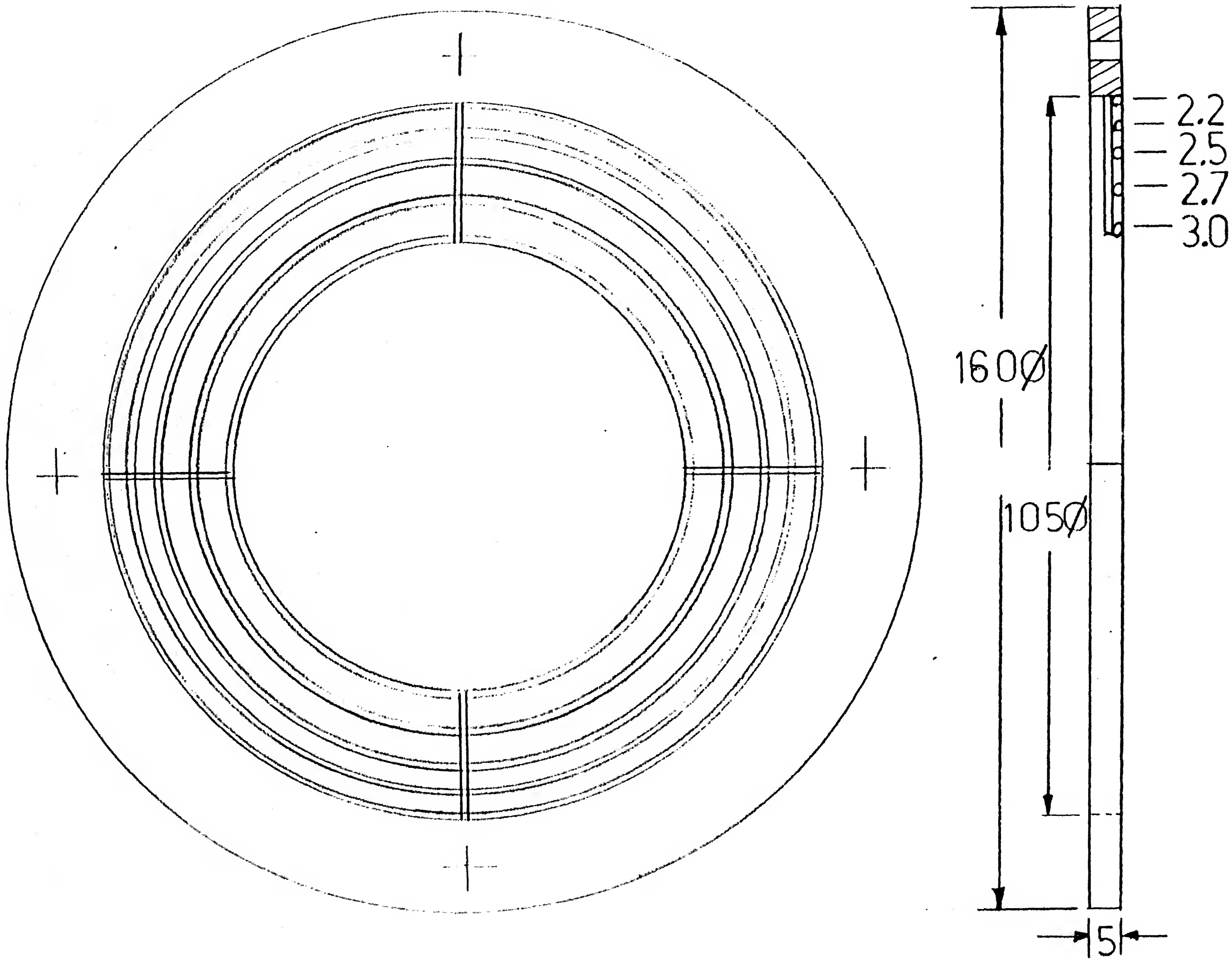


Fig. 9 Grid design

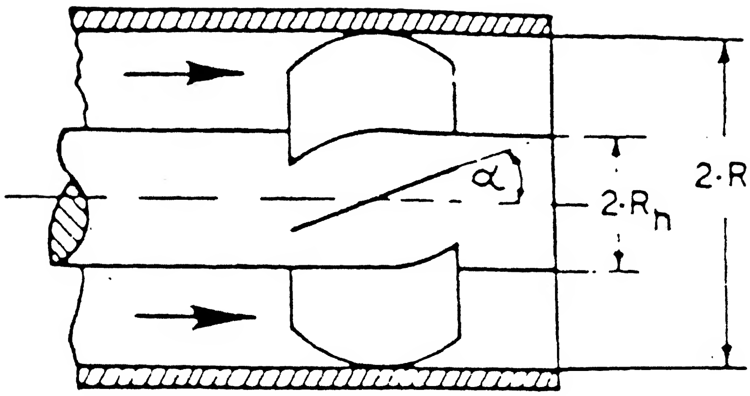


Fig. 10 Straight guide vane swirler

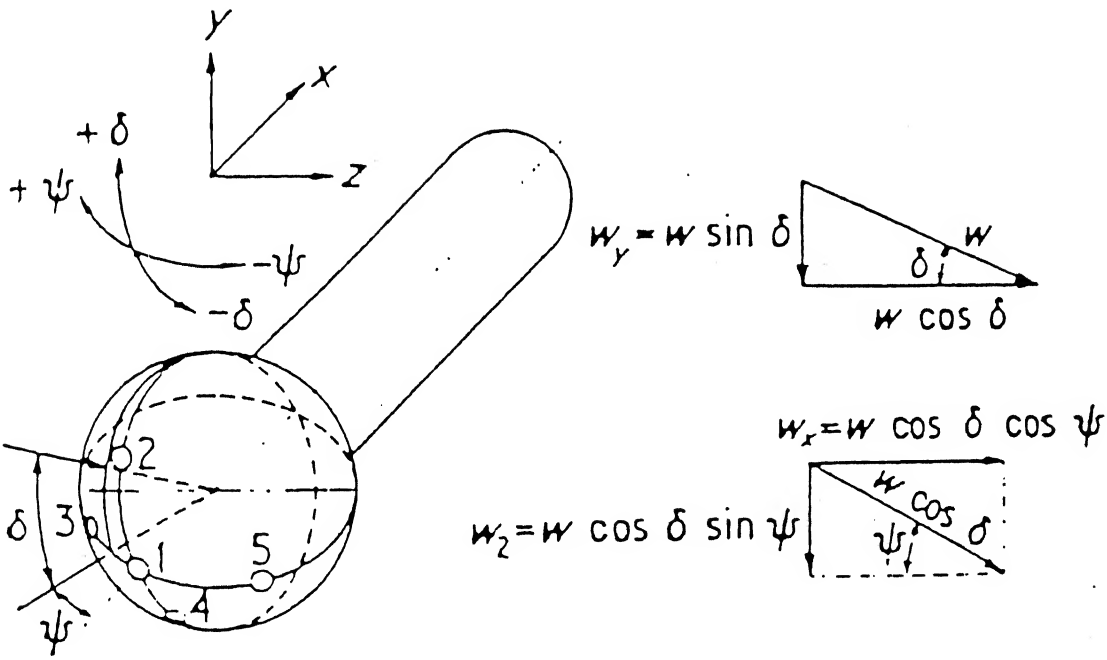


Fig. 11 Relation between yaw and pitch angle with velocity vector diagram

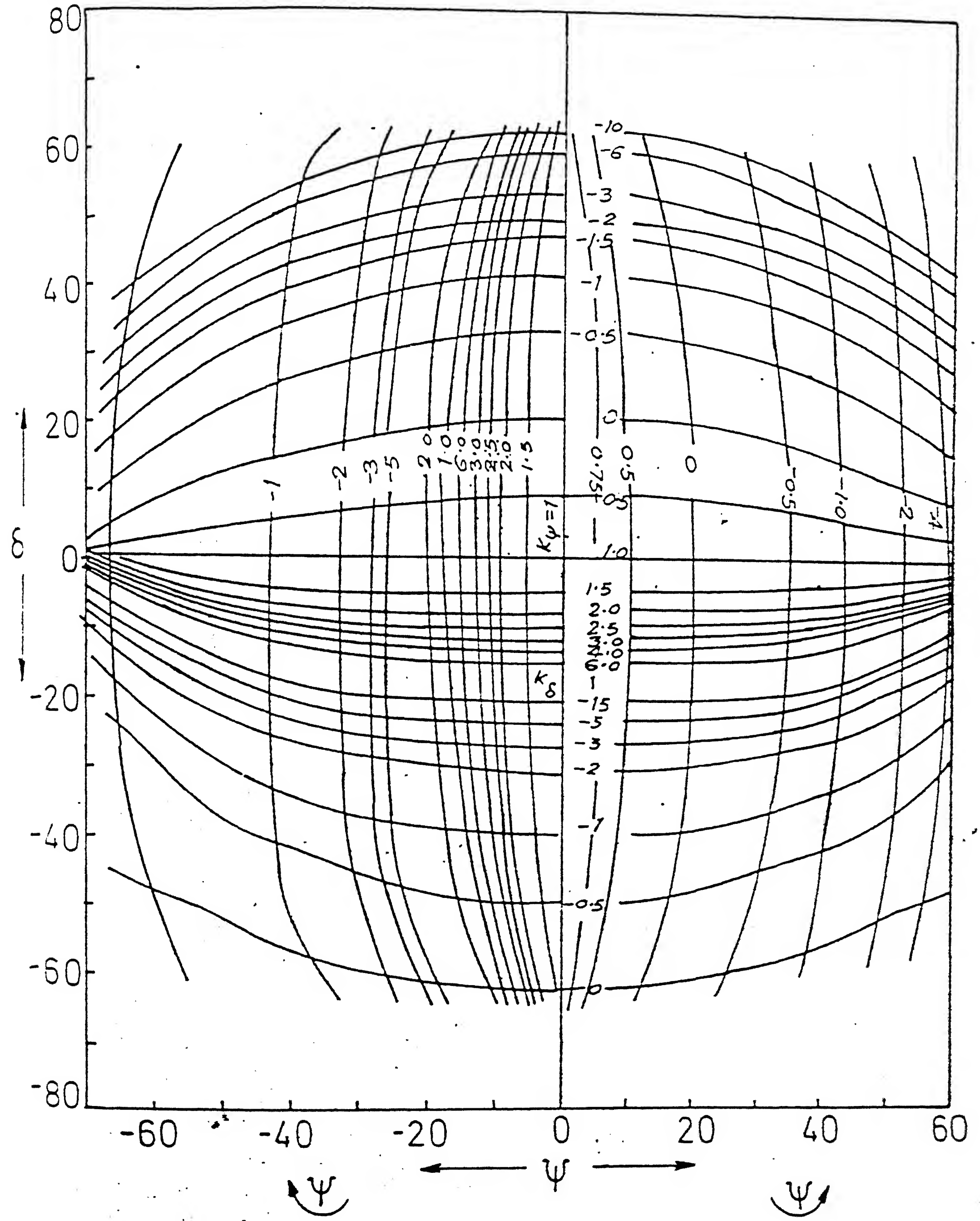


Fig. 12 Calibration curves for the inclination factor K_δ and K_ψ.

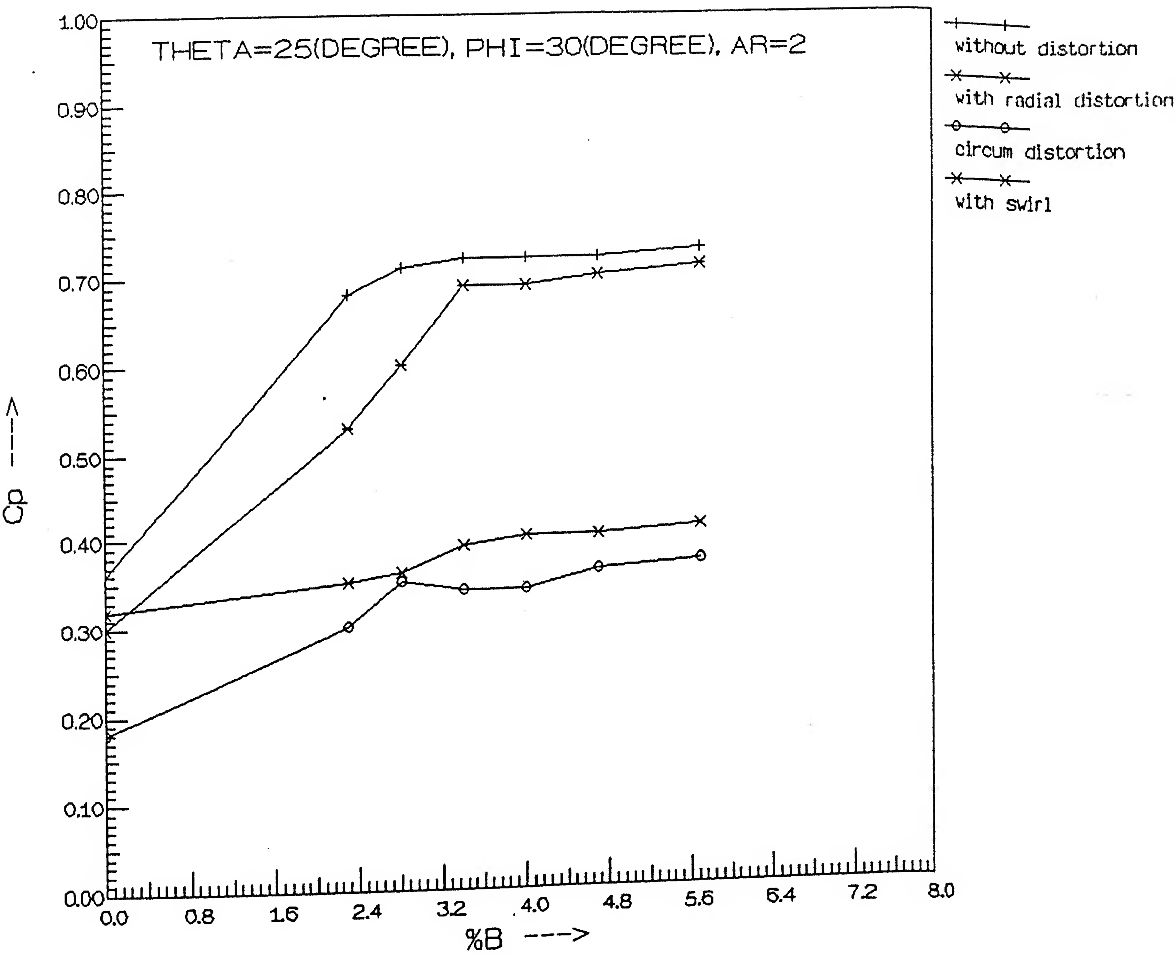
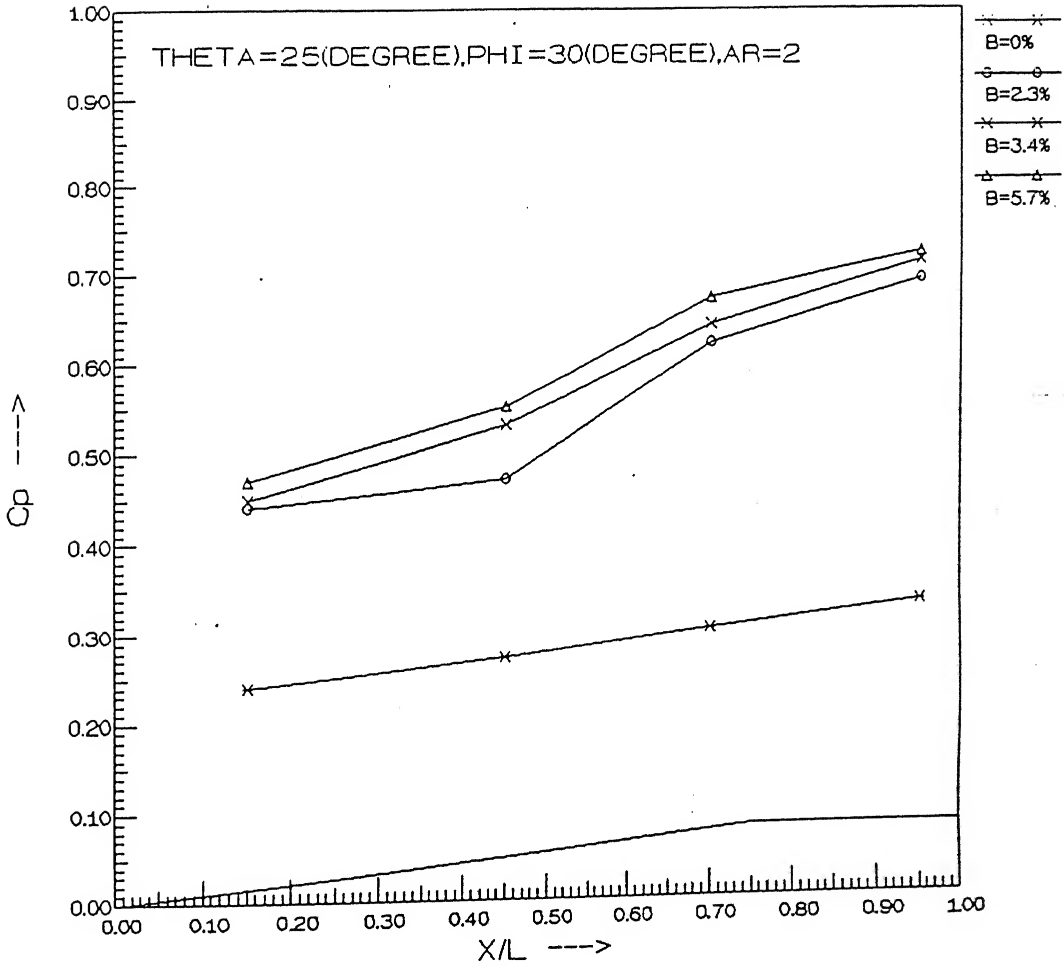


Fig. 13 Diffuser performance for different bleed offs



g. 14 Diffuser performance along the axial length with uniform inlet velocity profile

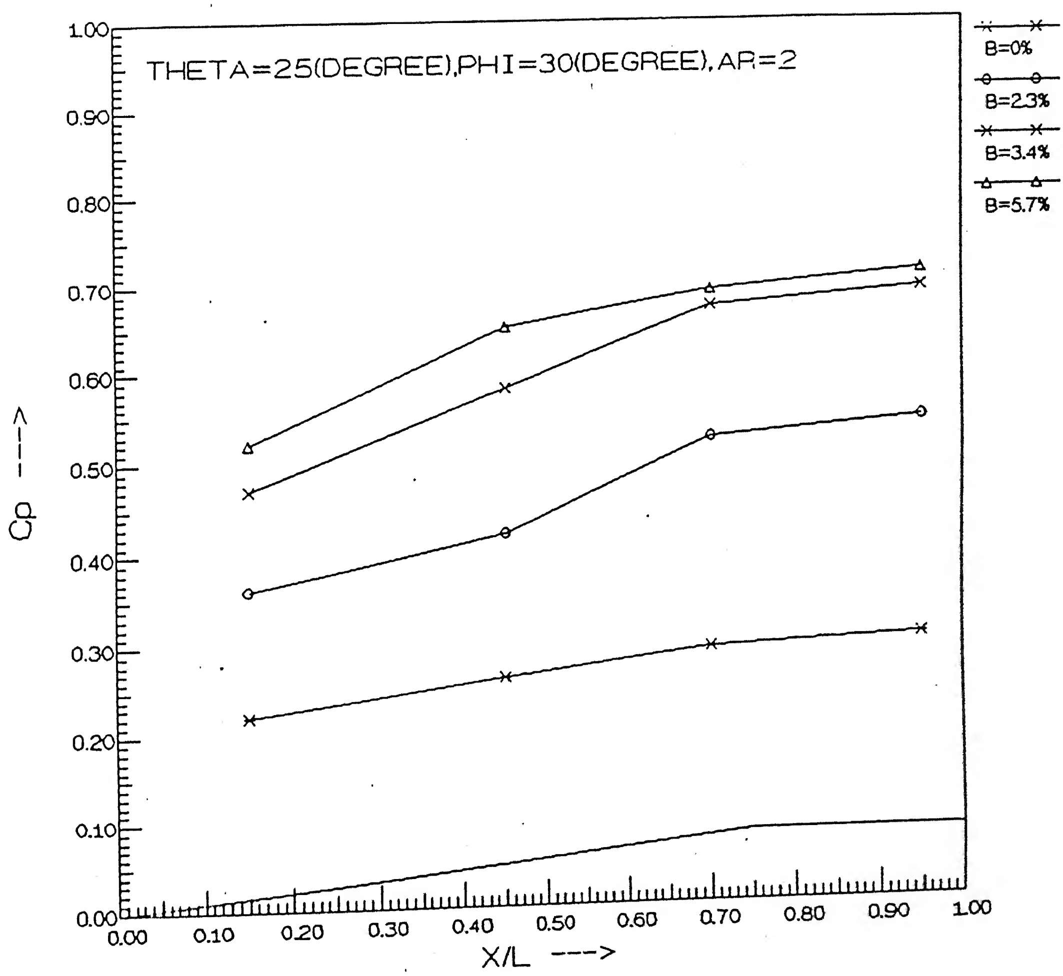


Fig. 15 Diffuser performance along the axial length with radial velocity distortion

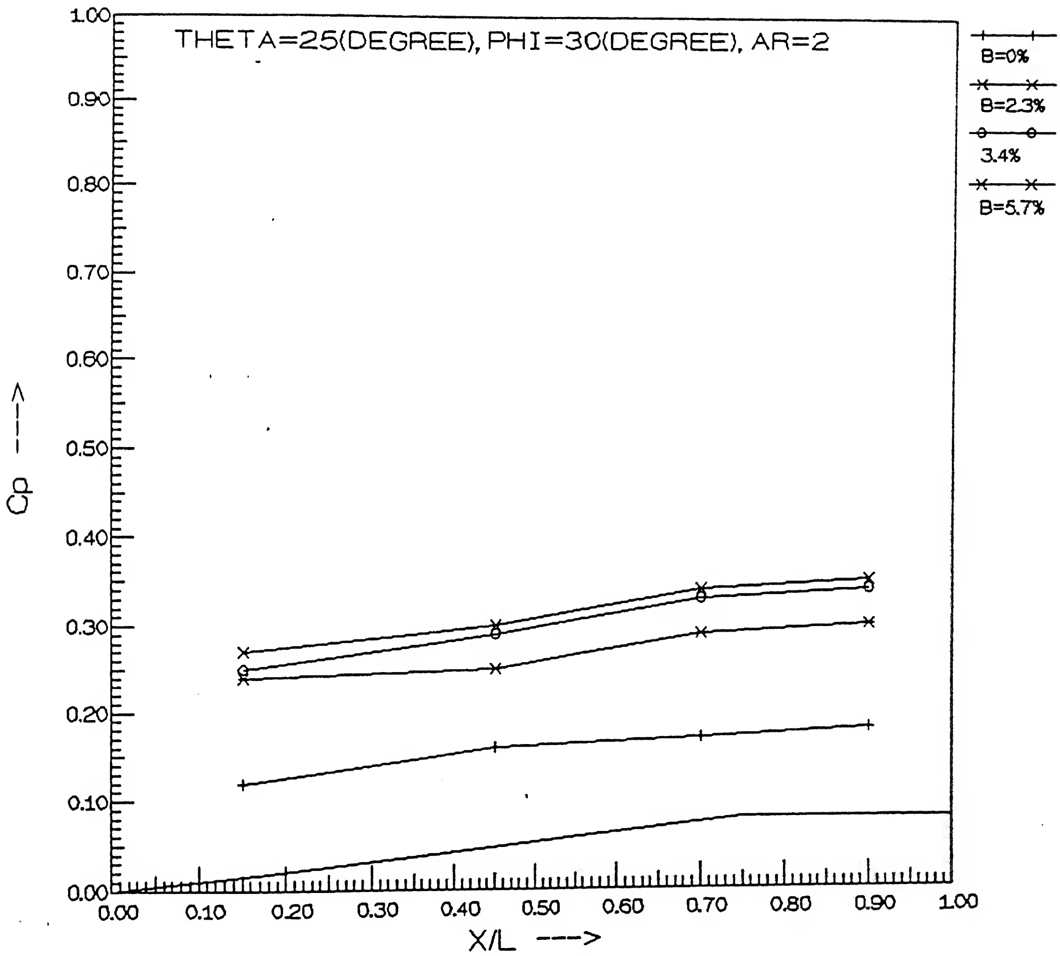


Fig. 16 Diffuser performance along the axial length with circumferential velocity distortion

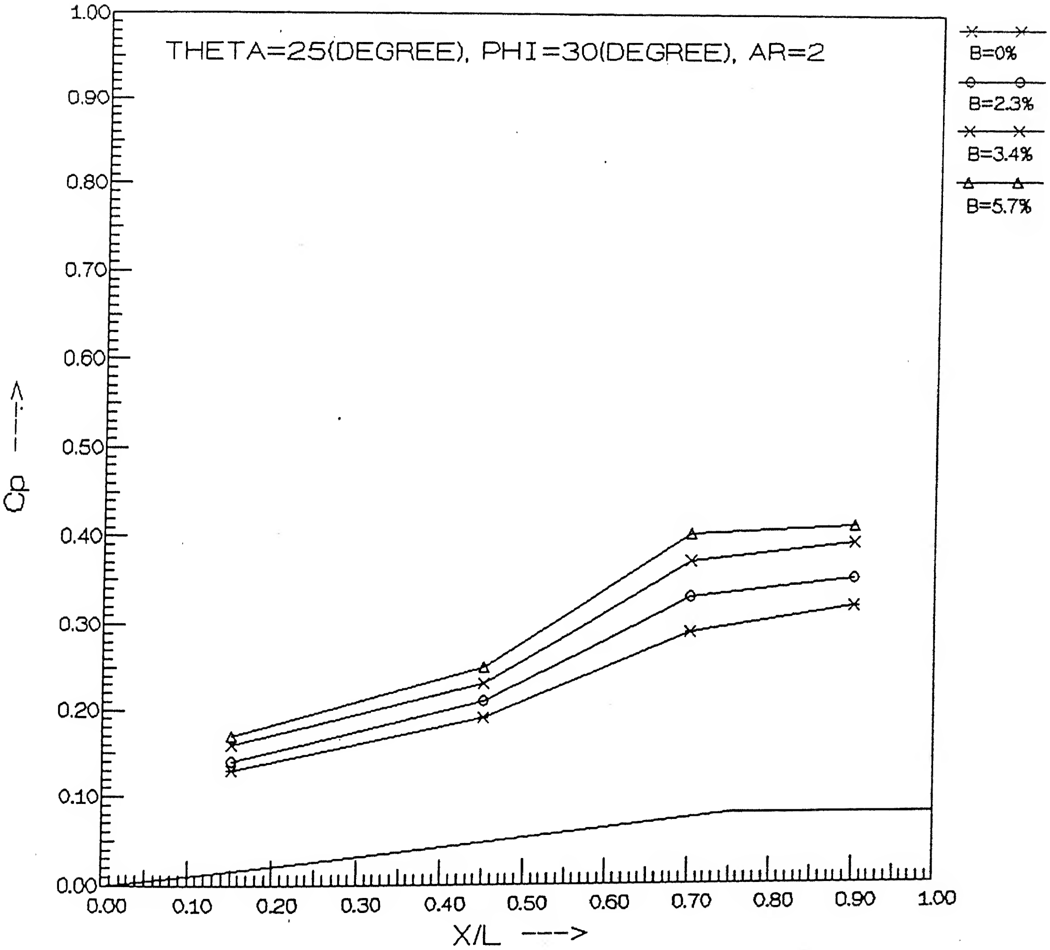


Fig. 17 Diffuser performance along the axial length with swirl at inlet

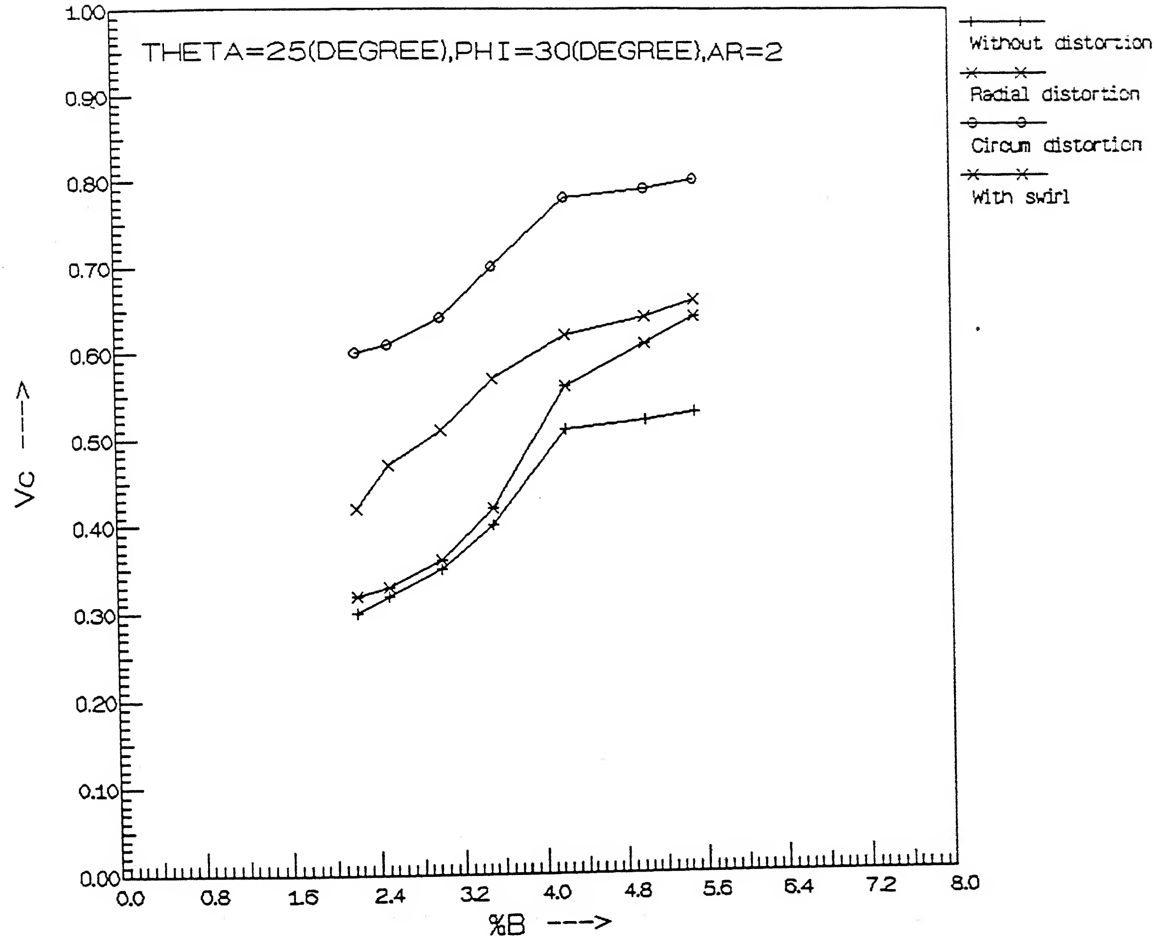


Fig. 18 Vortex chamber depression for different bleed of rates

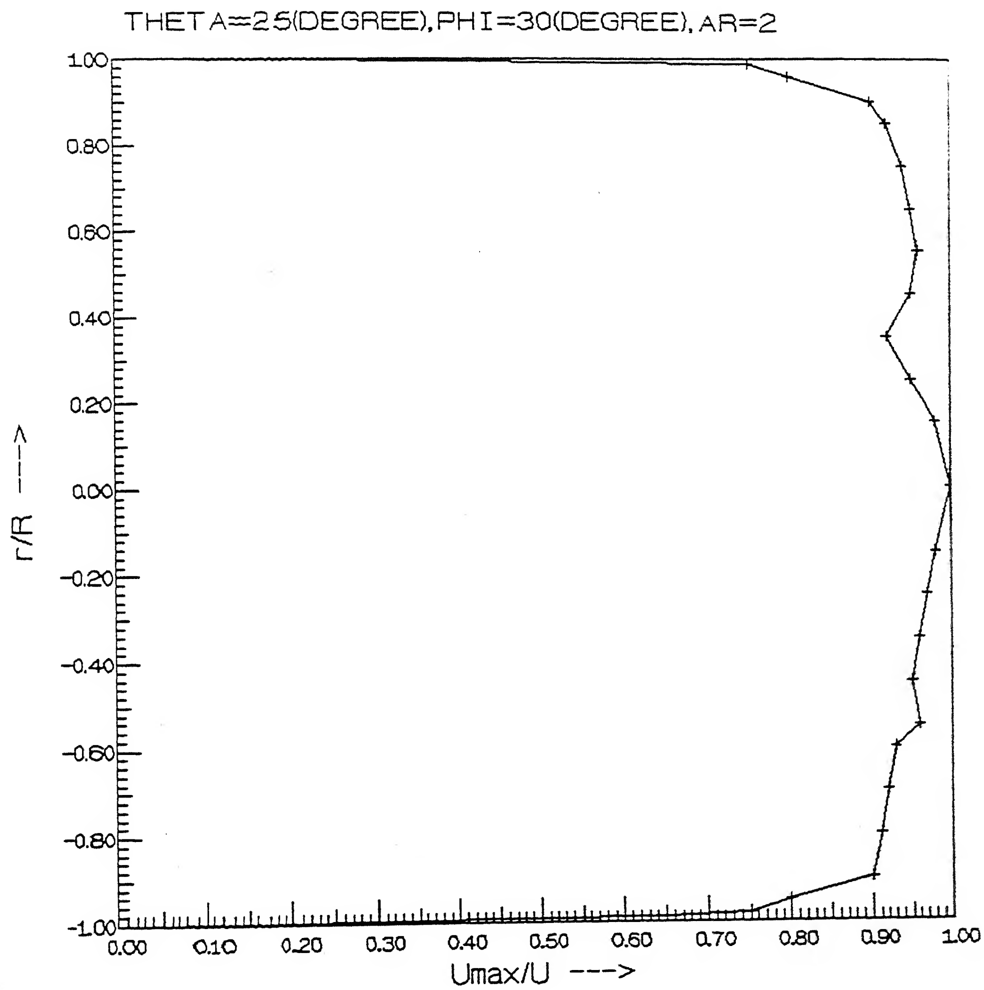


Fig. 19 Velocity profile at inlet without distortion

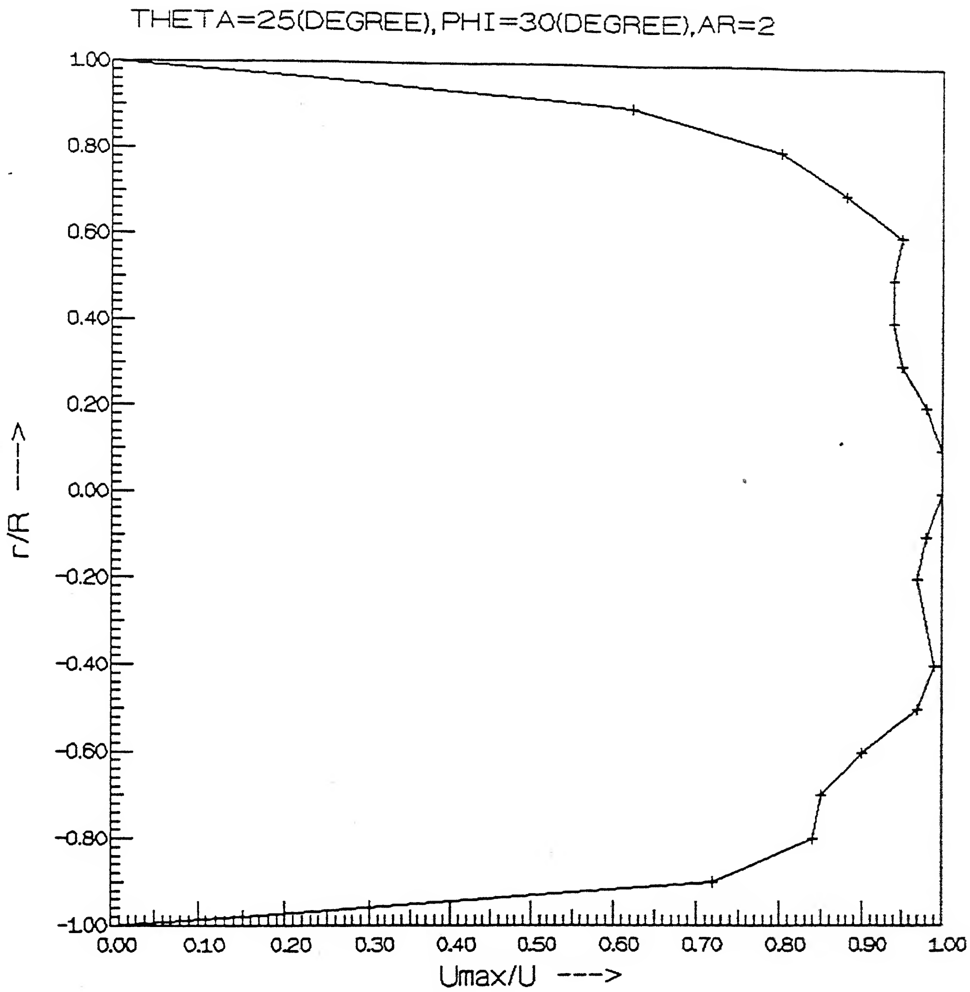


Fig. 20 Velocity profile at exit without suction

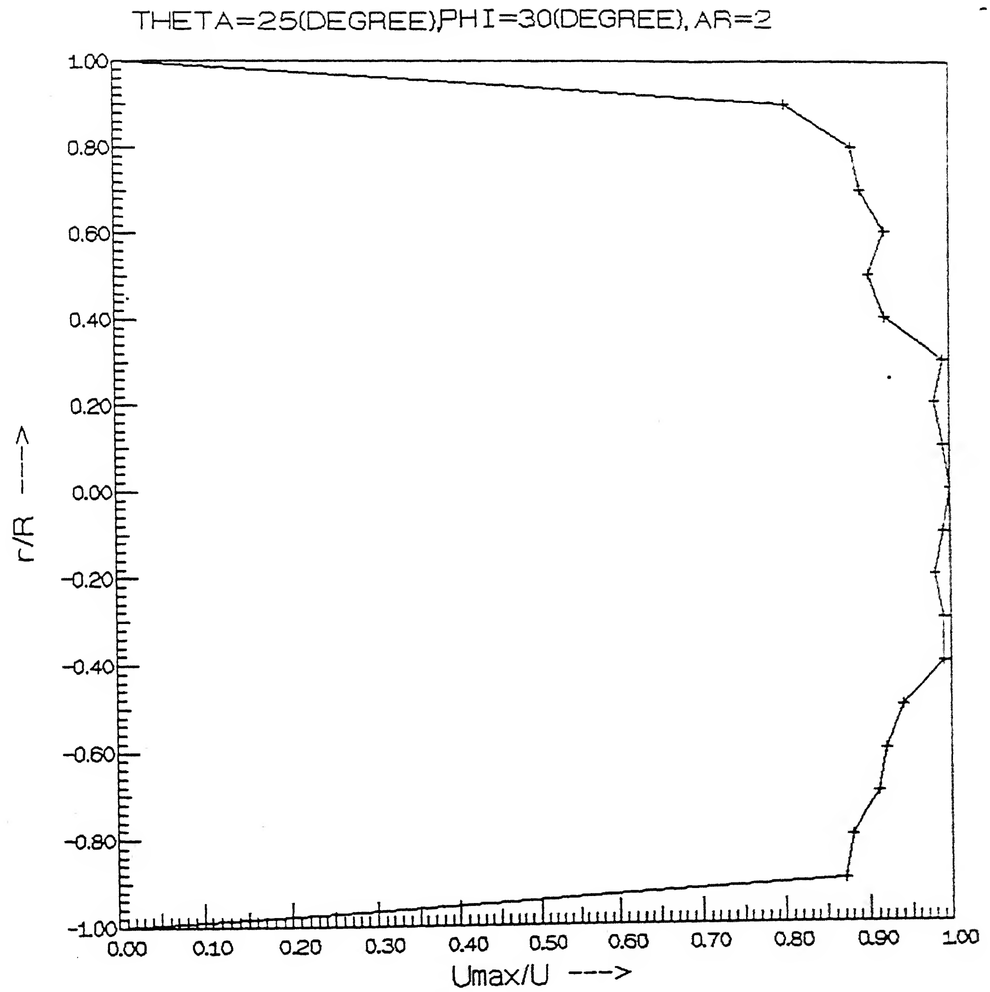


Fig. 21 Velocity profile at exit at 2.2% bleed off

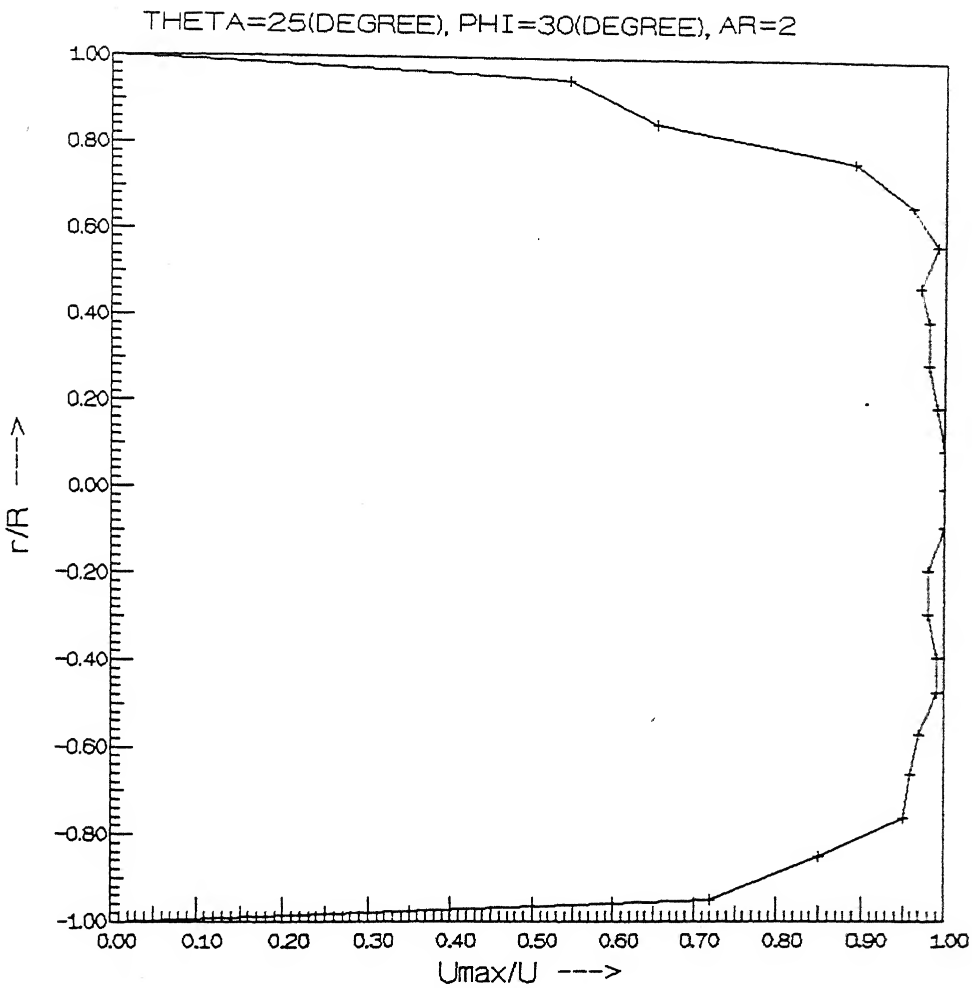


Fig. 22 Velocity profile at inlet with radial distortion

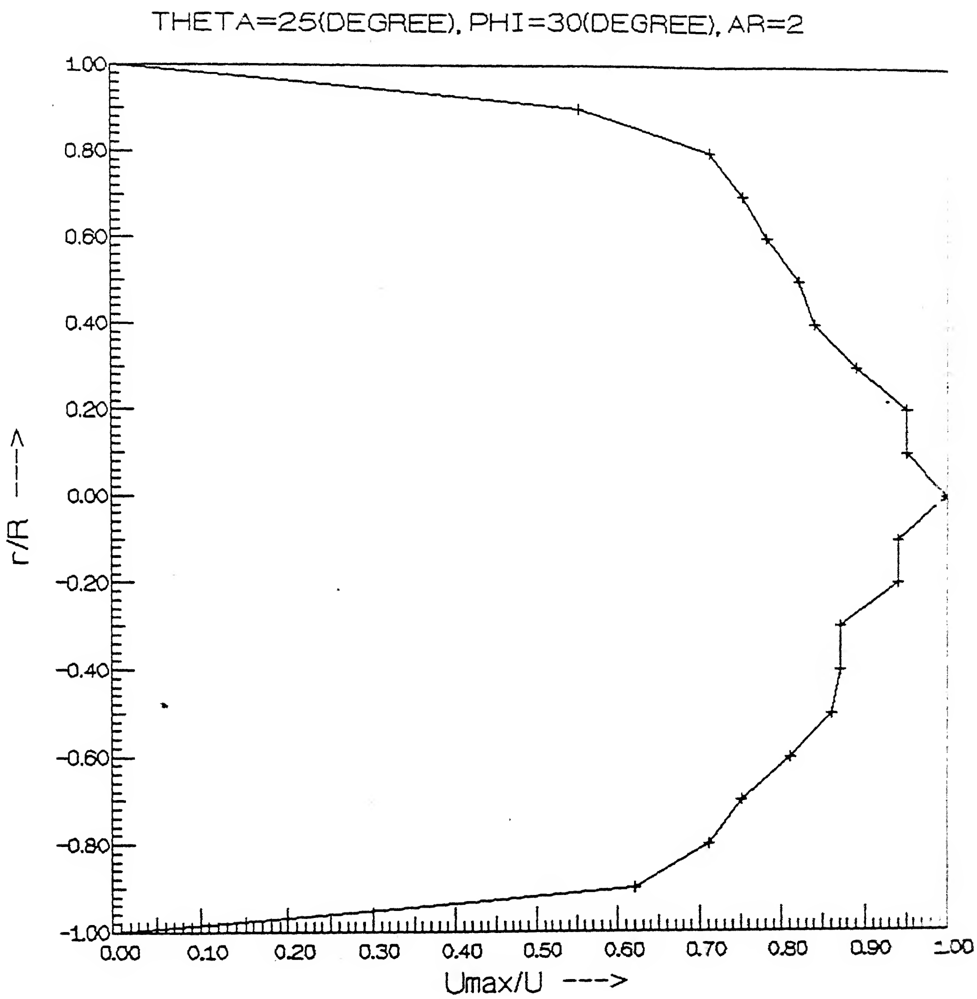


Fig. 23 Velocity profile at exit with radial distortion at 0% bleed off

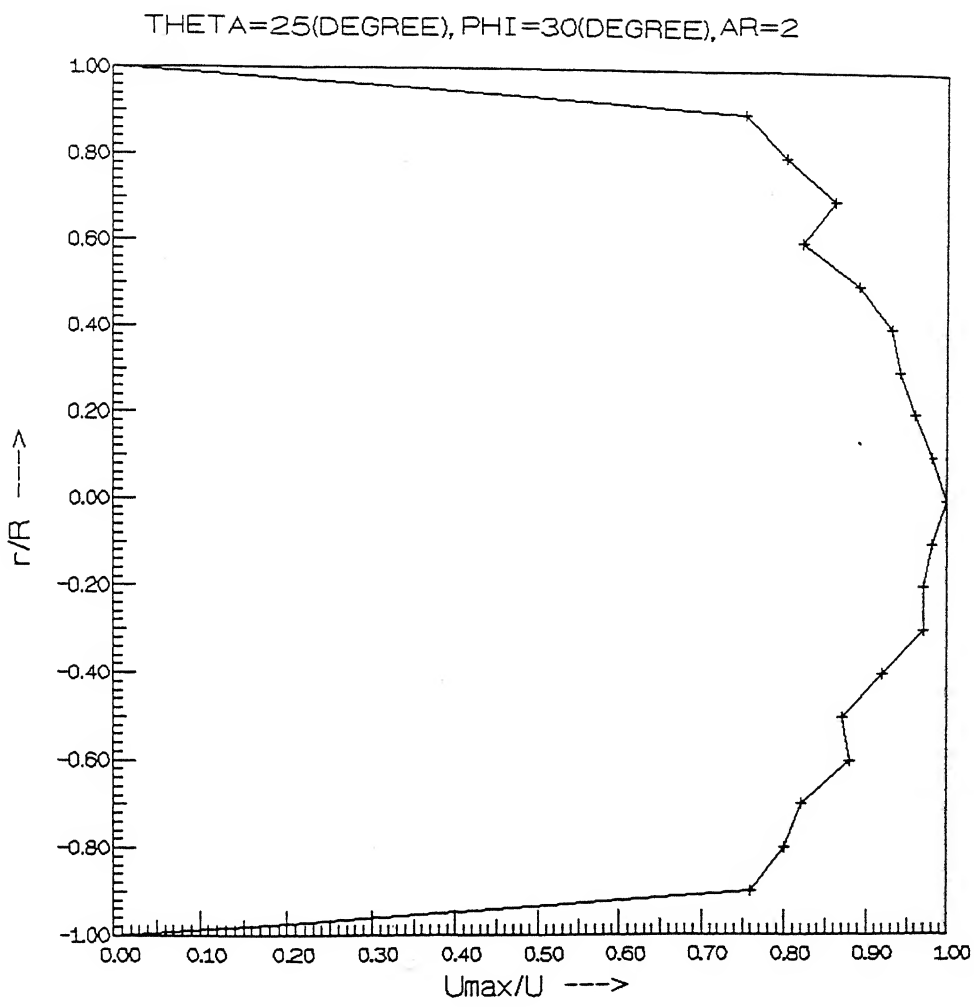


Fig. 24 Velocity profile at exit with radial distortion at 3.2% bleed off

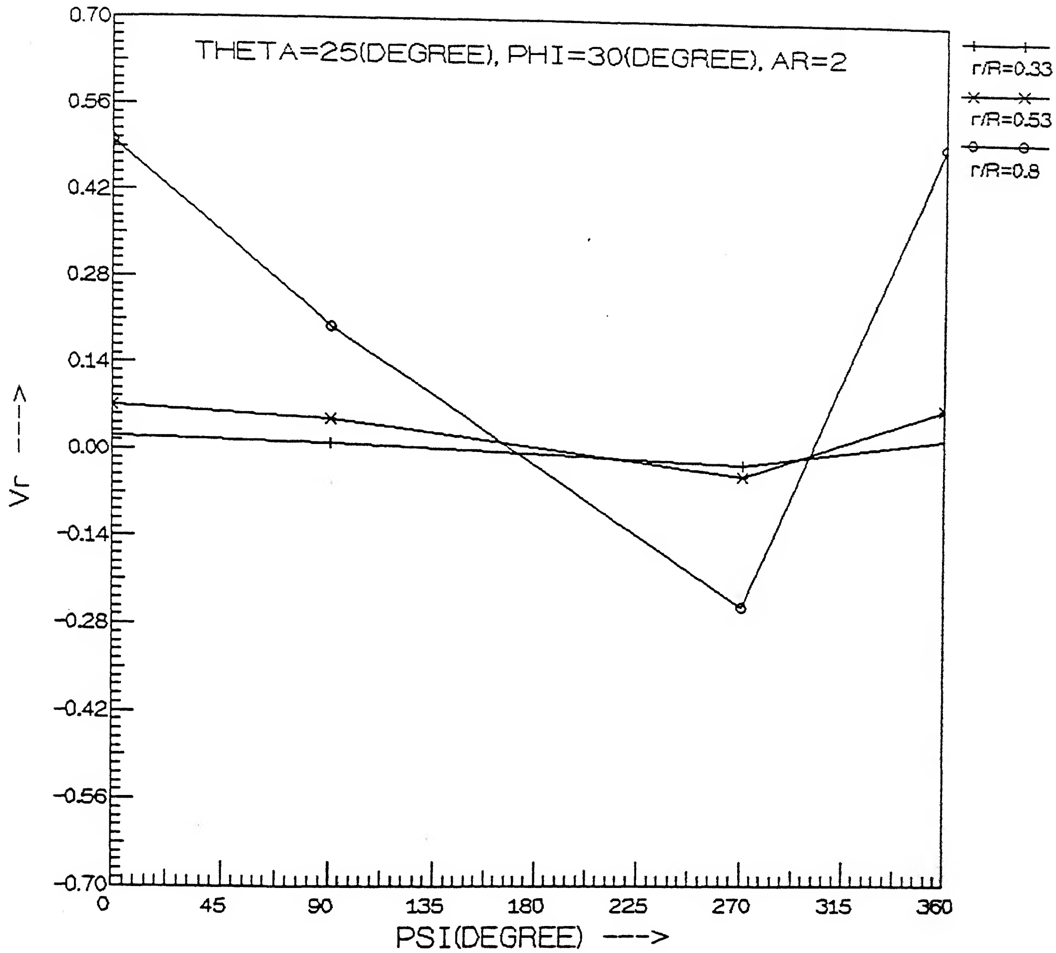


Fig. 25 Velocity profile at inlet with circumferential distortion

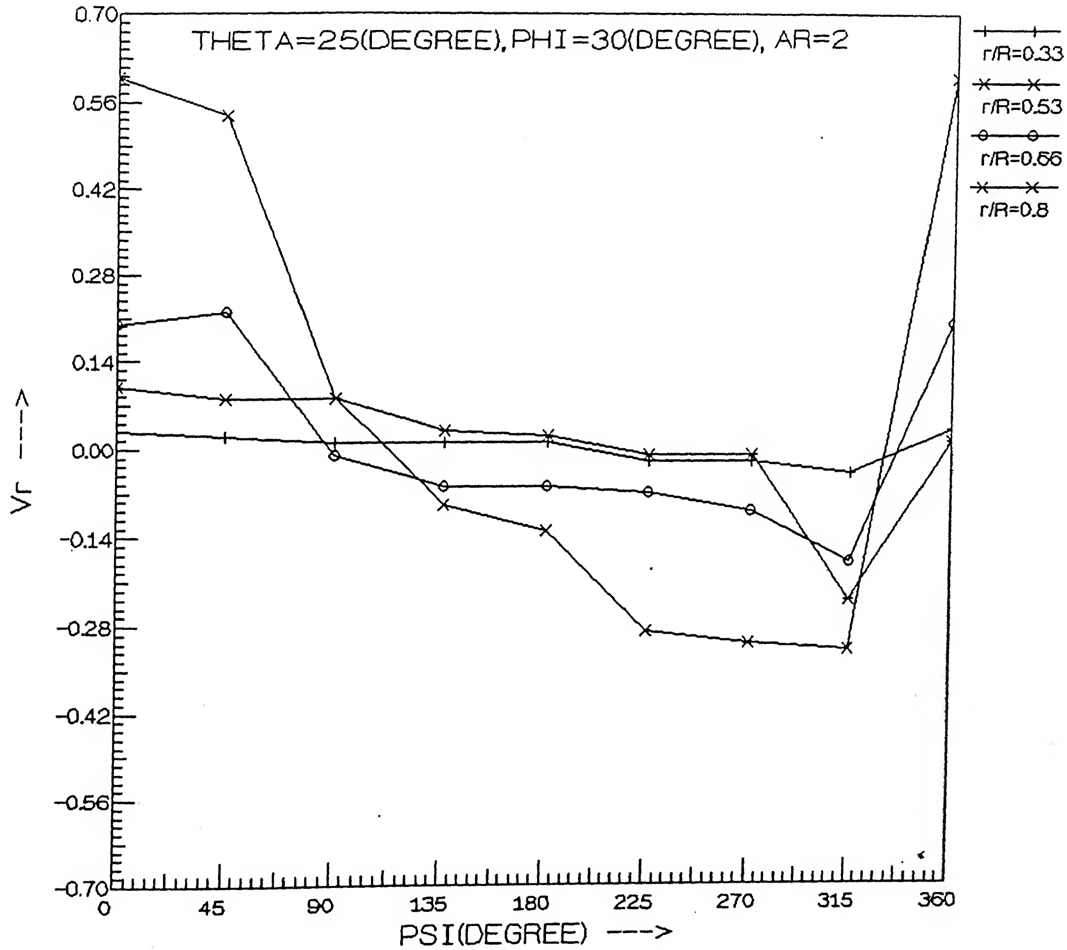


Fig. 26 Velocity profile at exit with circumferential at 0% bleed off

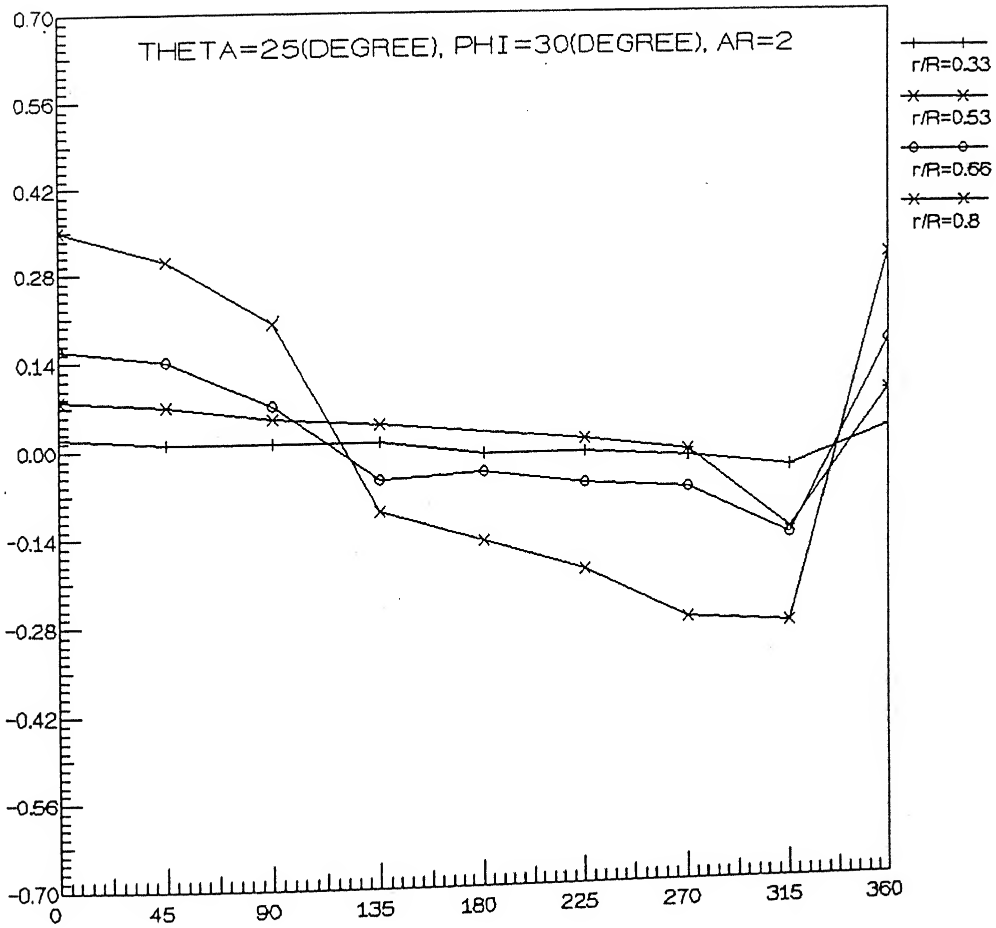


Fig. 27 Velocity profile at exit with circumferential distortion at 3% bleed off

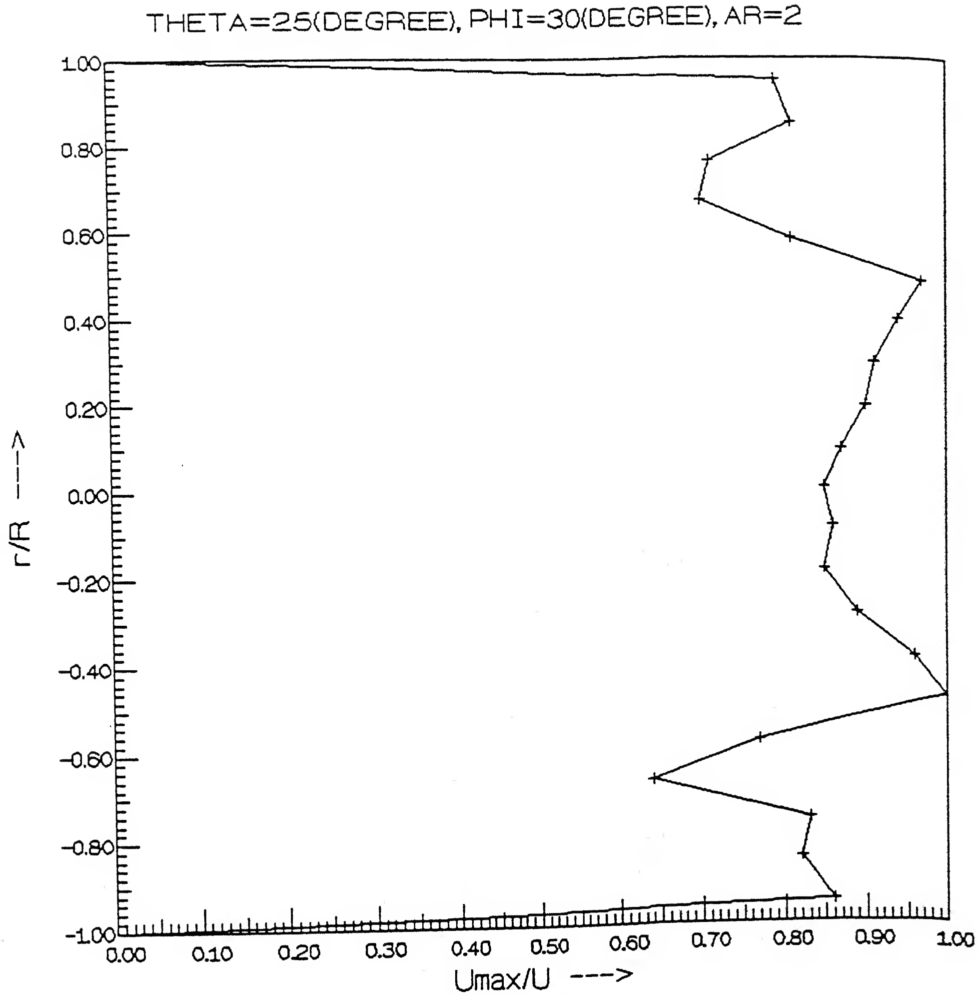


Fig. 28 Axial velocity profle at inlet with swirl

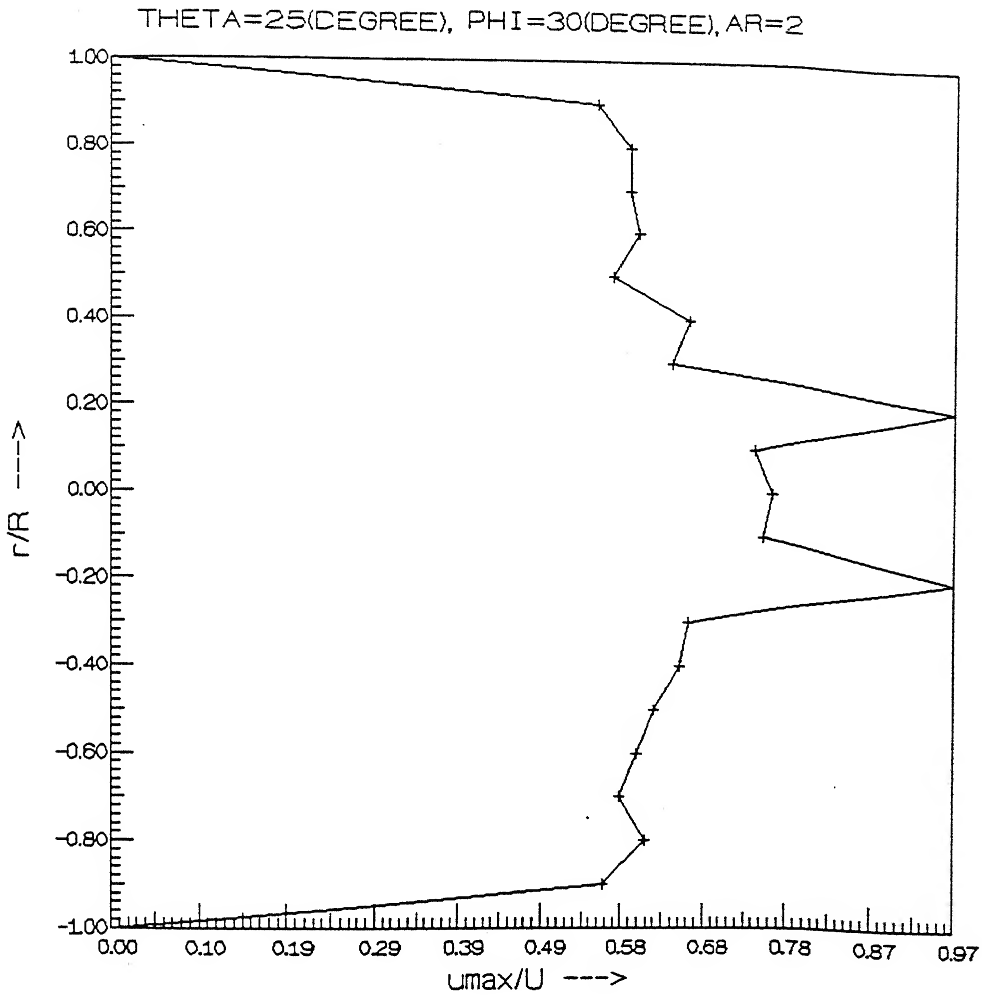


Fig. 29 Axial velocity profle at exit with swirl at 0% bleed off

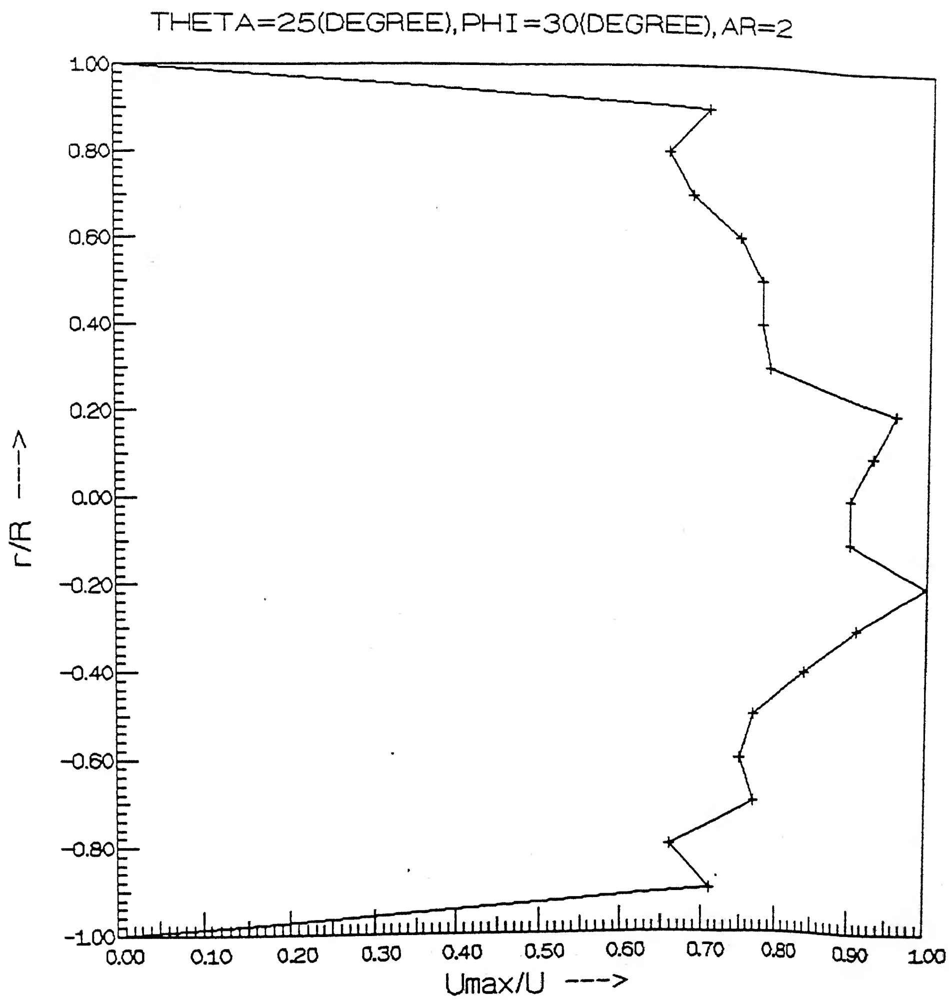


Fig. 30 Axial velocity profle at exit with swirl at 3.3% bleed off